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Climate Change Biology: Impacts on Species Distribution and Survival

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Abstract

Climate change represents one of the most profound drivers of biological reorganization in the Anthropocene, reshaping species distributions, disrupting ecological interactions, and accelerating extinction risk across terrestrial and aquatic ecosystems. This paper synthesizes current evidence on the physical, physiological, and ecological mechanisms through which climate change influences species survival and biodiversity patterns globally. Emphasis is placed on the role of extreme temperature events, particularly rising maximum temperatures, as primary determinants of local extinctions rather than gradual shifts in mean climate conditions. The paper further examines latitudinal and altitudinal range shifts, phenological mismatches, trophic asynchrony, and physiological constraints such as reduced thermal safety margins, especially in tropical and intertidal organisms. Case studies from amphibians, coral reefs, polar ecosystems, and forest and marine food webs illustrate the compounded effects of climate stressors interacting with habitat loss, disease, and altered species interactions. While phenotypic plasticity and rapid evolutionary responses can facilitate short-term persistence, their capacity is increasingly outpaced by the velocity of contemporary climate change. The paper highlights adaptive conservation strategies, including climate refugia, habitat connectivity, and assisted migration, as essential tools for mitigating biodiversity loss. Ultimately, effective biodiversity conservation under climate change will require integrated approaches combining rapid greenhouse gas mitigation with proactive, climate-informed ecological management.

Keywords Climate change biology; Species distribution shifts; Local extinction; Thermal safety margins; Phenological mismatch; Biodiversity conservation; Anthropocene; Adaptive management

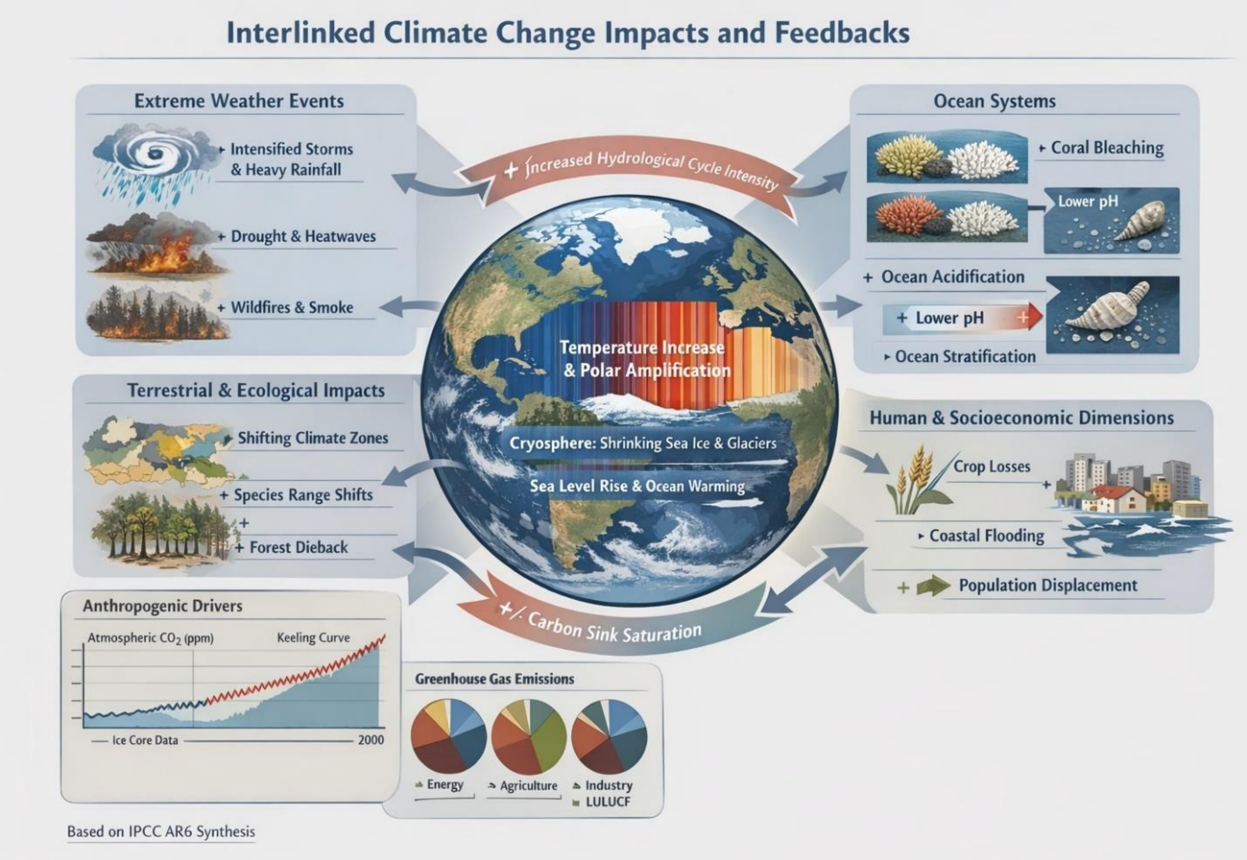
1. Introduction

The current geological epoch, frequently identified as the Anthropocene, is defined by an unprecedented shift in the Earth's climate system, primarily driven by the rapid accumulation of anthropogenic greenhouse gases (Anderson et al., 2012). While the planet has historically experienced cyclical climatic fluctuations, such as the Milankovitch cycles that operate over 100,000-year periods, the contemporary rate of change is distinguished by its velocity, which far exceeds the adaptive capacity of many biological lineages (Luedtke et al., 2023). Atmospheric carbon dioxide (CO2) concentrations, which fluctuated between 180 and 300 parts per million (ppm) for the last 800,000 years, have surged to over 415 ppm in the span of mere centuries (Thompson Rivers University, 2021). This chemical alteration of the atmosphere facilitates a pervasive greenhouse effect, where gases such as methane (CH4), nitrous oxide (N2O), and various fluorinated gases (F-gases) trap infrared radiation, leading to a rise in global mean surface temperatures of approximately 1.1 degrees Celsius (°C) since the industrial revolution (Intergovernmental Panel on Climate Change [IPCC], 2023). The resulting biological responses ranging from shifts in geographic distributions and phenological timing to catastrophic local extinctions represent a fundamental restructuring of the biosphere that threatens the stability of global biodiversity and ecosystem services (Bongaarts, 2019).

2. Physical and Chemical Drivers of Biological Reorganization

The biological impacts of climate change are rooted in the fundamental physics of the greenhouse effect. Specific atmospheric constituents, notably CO2, CH4, and N2O, absorb and re-emit longwave radiation, thereby insulating the planet (EPA, 2021). Carbon dioxide is the primary driver of this warming, released largely through the combustion of fossil fuels, industrial chemical reactions such as cement manufacturing, and the degradation of biological carbon sinks through deforestation (Urban, 2015). Methane, though shorter-lived in the atmosphere, possesses a significantly higher global warming potential and originates from both natural wetlands and human activities, including livestock agriculture and fossil fuel extraction (Kupiainen et al., 2022).

Figure 1. Systems-level Overview of Anthropogenic Drivers, Climate Feedbacks, and Multi-domain Ecological Impacts.



Based on IPCC AR6 Synthesis

The consequence of this warming is not uniform, manifesting as a suite of environmental changes that directly influence organismal survival. These include shifts in precipitation patterns, increases in ocean acidity, the rapid melting of glaciers and sea ice, and a heightened frequency of extreme weather events such as heatwaves, droughts, and floods (IPCC, 2022). Ocean acidification, a result of the ocean absorbing approximately 30% of anthropogenic CO2, decreases the saturation state of carbonate minerals, which is critical for the calcification of marine organisms such as corals and mollusks (Polidoro, 2025).

Table 1: Characteristics and Primary Sources of Major Anthropogenic Greenhouse Gases

Greenhouse Gas	**Primary Anthropogenic Sources**	**Atmospheric Lifespan**	**Contribution to Warming**
Carbon Dioxide (CO2)	Fossil fuel combustion, cement production, deforestation	Centuries to millennia	High (most abundant)
Methane (CH4)	Rice paddies, livestock, fossil fuel leaks, landfills	~12 years	Significant (high potency)
Nitrous Oxide (N2O)	Agricultural fertilizers, industrial processes	~114 years	Moderate
Fluorinated Gases (F-gases)	Refrigerants, aerosols, semiconductor manufacturing	Weeks to thousands of years	Variable (extremely high GWP)

3. Mechanistic Drivers of Species Extinction

The identification of specific climatic variables that trigger local extinctions is paramount for predicting future biodiversity loss. Recent meta-analyses covering 538 plant and animal species globally indicate that local extinctions are most strongly associated with increases in maximum annual temperatures (Tmax) rather than changes in mean annual temperature (Tmean) (Román-Palacios & Wiens, 2020). Populations that underwent local extinction were located at sites where the hottest yearly temperatures increased roughly three times faster than at sites where populations persisted. Specifically, the mean increase in Tmax at extinction sites was 0.413 °C compared to 0.147 °C at non-extinction sites (Holzmann et al., 2022).

This finding suggests that acute thermal stress, rather than gradual shifts in average conditions, is the primary demographic driver of population collapse. In temperate regions, this pattern is even more pronounced, with extinction sites showing smaller changes in Tmean but significantly larger spikes in Tmax (Wiens, 2016). This paradox highlights the inadequacy of using annual averages as proxies for biological risk, as organisms are more likely to be limited by their physiological tolerance to extreme heat events (Panetta et al., 2018).

3.1 The Role of Dispersal and Niche Shifts in Survival

To persist under changing climates, species must either relocate to suitable environments or adjust their ecological niches to tolerate novel conditions. Ecological niche modeling suggests that if species rely solely on dispersal to track their preferred climate, between 57% and 70% of those studied could face extinction by 2070 because the velocity of climate change exceeds their natural migration rates (Bates et al., 2021). However, the capacity for niche shifts defined as the set of temperature and precipitation conditions where a species can occur can mitigate this risk (Årevall et al., 2018). When both dispersal and niche shifts are considered, projected extinction rates drop to between 16% and 30% (Thompson et al., 2019). This underscores the critical importance of phenotypic plasticity and evolutionary adaptation in determining the future landscape of biodiversity (Mestre et al., 2020).

4. Spatial Redistribution of Biodiversity

The most pervasive biological signature of global warming is the systematic redistribution of species across the planet. As the thermal envelopes of organisms move poleward and upward, species are tracking these isotherms to remain within their physiological limits (Chen et al., 2011).

4.1 Latitudinal and Altitudinal Range Shifts

Meta-analytical evidence confirms that species are shifting toward higher latitudes at a median rate of 16.9 kilometers per decade and toward higher elevations at a rate of 11.0 meters per decade (Visser & Gienapp, 2019). These movements are not uniform across taxa; birds, insects, and marine fish demonstrate the most rapid latitudinal shifts, while mammals often lag behind, possibly due to habitat fragmentation or lower dispersal capacities (Spence et al., 2020). In marine ecosystems, where physical barriers are fewer, species often track their thermal niches more accurately than terrestrial organisms (Lenoir & Svenning, 2015).

The dynamics of these shifts are characterized by "leading-edge expansion" and "trailing-edge contraction". At the leading edge, vagile species colonize new territories that have recently become thermally suitable (Pinsky et al., 2020). Conversely, at the trailing edge (the warmer limit of the range), populations face extirpation as conditions exceed their survival thresholds (Brown, 2022). For example, freshwater fish populations at their equatorward limits are showing significant declines in abundance as stream temperatures rise, while populations at their poleward limits are expanding (Luedtke et al., 2023).

Table 2: Observed Latitudinal and Altitudinal Range Shifts by Major Taxonomic Groups

Taxonomic Group	Median Latitudinal Shift (km/decade)	Median Altitudinal Shift (m/decade)	Sensitivity to Tmean
Birds	17.0	1.0	High (Vagile)
Insects (Butterflies)	18.0	12.0	High (Thermo-sensitive)
Mammals	0.0	10.0	Low (Dispersal limited)
Marine Fish	20.0+	N/A (Depth: 1.0 m/yr)	Very High
Terrestrial Plants	1.5	11.0	Moderate

4.2 Multidimensional and Unexpected Shifts

While the poleward/upward paradigm is a dominant trend, recent research has uncovered "unexpected" range shifts toward the equator or lower elevations. These anomalies are often driven by complex interactions between temperature and precipitation (Wernberg et al., 2025). In Australia, a study of 464 bird species revealed that shifts were often multidimensional (east-west or equatorward) when accounting for moisture availability, as species prioritized tracking suitable rainfall patterns over temperature alone (Rubenstein et al., 2023). Furthermore, localized shifts can be influenced by land-use changes and the availability of microhabitats, which can buffer organisms from regional warming (Alarcón et al., 2018).

5. Phenological Dynamics and Trophic Asynchrony

Climate change is fundamentally altering the temporal structure of ecosystems by shifting the timing of life-cycle events, a phenomenon known as phenology (Renner & Zohner, 2018). These shifts, however, occur at unequal rates across different taxa, leading to phenological "mismatches" or trophic asynchrony (Visser & Gienapp, 2019).

5.1 Mechanisms of Mismatch

Mismatches typically occur in consumer-resource interactions where the peak demand of the consumer (e.g., a predator or pollinator) no longer aligns with the peak abundance of its resource (e.g., prey or flowers) (González-Tokman et al., 2020). This divergence is often driven by different species responding to different environmental cues. For instance, many plants and insects are highly sensitive to temperature (thermo-period), while many migratory birds and some mammals are constrained by day length (photoperiod) (Kellermann et al., 2019).

When spring temperatures rise, temperature-sensitive organisms advance their timing significantly faster than photoperiod-dependent ones (Legris et al., 2017). This can result in a "yardstick" mismatch, where insectivorous birds hatch their chicks after the peak of caterpillar abundance, leading to reduced fledgling weight and lower survival rates (Segar et al., 2019). In marine environments, the "match-mismatch hypothesis" explains how the survival of fish larvae depends on the synchrony of their emergence with seasonal plankton blooms, both of which are being decoupled by warming ocean temperatures (Gotthard et al., 2025).

5.2 Impact on Mutualisms and Antagonistic Interactions

The consequences of mismatch vary between mutualistic and antagonistic interactions. In mutualisms, such as plant-pollinator networks, a mismatch can harm both partners: the plant suffers from reduced reproductive success (pollen limitation), while the pollinator faces a shortage of floral resources (Rodríguez-Rodríguez et al., 2017). A study on Viola species and their solitary bee pollinators in the eastern United States demonstrated an increased risk of secondary extinction at higher latitudes, where climate-driven shifts are more severe (PNAS, 2025).

In antagonistic interactions, a mismatch may initially favor one species over the other, but long-term instability often leads to population declines. A classic example is the European larch bud moth, whose populations have collapsed in the European Alps because the larch trees now flush their leaves too early for the moth larvae to feed effectively, disrupting a 1,000-year cycle of population peaks (Montesinos-Navarro et al., 2017).

6. Physiological Underpinnings of Vulnerability

The susceptibility of an organism to climate change is determined by its physiological limits and its capacity for thermoregulatory behavior. For ectotherms, which comprise the majority of animal diversity, body temperature (Te) is governed by the environment rather than internal metabolic processes (Sunday et al., 2014).

6.1 Thermal Safety Margins (TSM) and Operative Temperatures

The "thermal safety margin" is the difference between a species' critical thermal maximum (CTmax) and the temperatures it experiences in the field. Traditionally, TSMs were calculated using ambient air temperatures (Ta), which often suggested a high degree of safety (McIntire, 2025). However, recent research utilizing "operative body temperatures" the theoretically equilibrated body temperature of an organism in a specific microhabitat reveals a more precarious reality (Rafferty et al., 2015). Operative temperatures in sun-exposed habitats can exceed air temperatures by more than 20 °C, meaning many ectotherms effectively have zero or negative physiological safety margins and must rely entirely on behavioral cooling (e.g., seeking shade or burrows) to survive the hottest hours (Chou et al., 2019).

6.2 Tropical Vulnerability and Latitudinal Patterns

A significant finding in macrophysiology is that tropical species are often more vulnerable to warming than temperate ones, despite experiencing lower rates of climate change (Sheldon 2019).

Tropical ectotherms have evolved in stable environments and thus possess narrower thermal niches and CTmax values that are closer to their daily temperature maxima. Temperate species, conversely, have broader thermal niches to accommodate seasonal extremes, providing them with larger TSMs (Monge et al., 2023). As the climate warms, tropical species have less "physiological room" to adapt, increasing their risk of heat-induced mortality (Pollock et al., 2021).

Table 3: Comparison of Thermal Safety Margins (TSM) and Physiological Vulnerability Across Environments

Environmental Context	**TSM (CTmax - Ta)**	**TSM (CTmax - Te)**	**Behavioral Reliance**	**Vulnerability Rank**
Tropical Lowlands	Moderate (5-10 °C)	Negative/Zero	Essential	High
Temperate Forests	High (15-20 °C)	Low (2-5 °C)	Moderate	Moderate
Alpine/Arctic	Very High	Variable	Seasonal	Moderate/High
Marine Intertidal	Low	Negative	Critical	Extreme

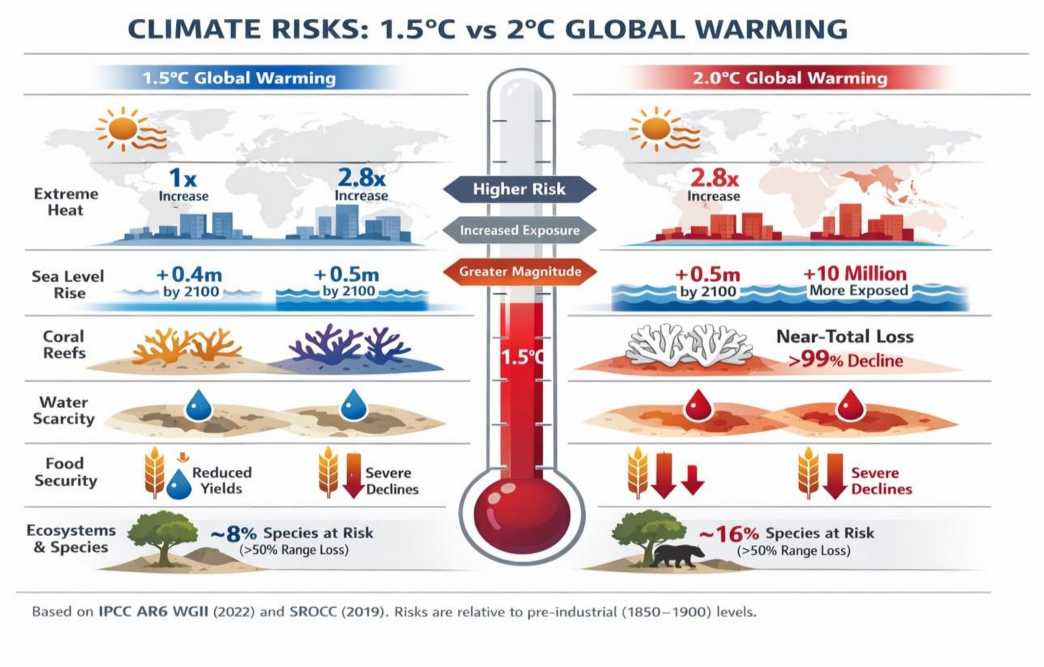
7. Case Studies of Heightened Extinction Risk

Specific groups of organisms are facing critical bottlenecks due to their unique physiological traits and the synergistic effects of climate change with other stressors (Allen et al., 2016).

7.1 Amphibians: A Convergence of Threats

Amphibians are the most threatened vertebrate class, with 41% of species categorized as threatened on the IUCN Red List. Their vulnerability stems from their highly permeable skin, which is necessary for gas exchange but makes them extremely sensitive to desiccation and pollutants (Lucas et al., 2024). Furthermore, rising temperatures increase their basal metabolic rate, which can lead to energy deficits if prey availability does not increase proportionally (Reference Collection, 2025). Climate change also acts synergistically with diseases, such as the chytrid fungus (Batrachochytrium dendrobatidis), by weakening amphibian immune systems or altering the environmental suitability for pathogens (Harfoot et al., 2021).

Figure 2 Comparative Analysis of Biological and Socioeconomic Risks Under 1.5°C and 2.0°C Global Warming Scenarios.



Based on IPCC AR6 WGII (2022) and SROCC (2019). Risks are relative to pre-industrial (1850–1900) levels.

7.2 Coral Reefs and Marine Heatwaves

Warm-water coral reefs are undergoing mass mortality events due to marine heatwaves. High water temperatures trigger bleaching, where corals expel their symbiotic zooxanthellae, leading to starvation and death of the coral polyps (EPA, 2021). A global assessment in 2024 showed that 44% of warm-water reef-building coral species are now threatened with extinction. This loss triggers a top-down and bottom-up collapse of reef ecosystems, as the physical structure of the reef which supports 25% of marine life deteriorates (Polidoro, 2025).

7.3 Polar and High-Latitude Ecosystems

Arctic and Antarctic fauna, particularly polar bears, seals, and penguins, are facing rapid habitat loss as sea ice retreats. Polar bears depend on sea ice for hunting seals; as ice-free periods lengthen, their ability to accumulate fat reserves is compromised (Faunalytics, 2016). In the Arctic, this loss of ice also reduces the production of ice algae, the foundational energy source for the entire marine food web, leading to bottom-up trophic cascades that affect zooplankton, fish, and marine mammals (McMeans et al., 2013).

8. Trophic Cascades and Ecosystem-Level Disruptions

The impacts of climate change on individual species ripple through food webs, often triggering trophic cascades that fundamentally alter ecosystem function (Hansen, 2020).

8.1 Arctic and Boreal Cascades

In the Arctic, the melting of sea ice reduces polar bear hunting grounds, which can lead to a release of predation pressure on seals. An increase in seal populations may subsequently lead to over-predation on fish stocks, impacting fisheries and other marine wildlife (Hamilton et al., 2017). In boreal and temperate forests, rising temperatures and droughts weaken trees, making them more susceptible to outbreaks of spruce bark beetles (Wege et al., 2025). Massive tree die-offs alter forest structure, reducing carbon sequestration capacity and removing habitat for countless herbivores and their predators (Adeniran-Obey et al., 2024).

8.2 Marine Kelp Forests and Urchin Barrens

In temperate marine ecosystems, the combination of ocean warming and the decline of apex predators (like sea otters) has facilitated the explosion of sea urchin populations. These "urchin barrens" occur when urchins overgraze kelp forests, leading to a total loss of complex vertical habitat and a collapse in biodiversity (Smith, 2021). This state shift from a highly productive kelp forest to a barren substrate is often difficult to reverse, as the urchins can persist in a low-energy state for years (Sustainability Directory, 2025).

9. Evolutionary and Plastic Mechanisms of Persistence

The survival of populations in the Anthropocene depends on the interplay between phenotypic plasticity and evolutionary adaptation (Ling et al., 2024)

9.1 The Role of Phenotypic Plasticity

Phenotypic plasticity the capacity of a single genotype to express different phenotypes in response to the environment is a critical "rapid-response" mechanism that can "buy time" for populations (Anderson et al., 2012). Plasticity is treated by many researchers as the "null model" for how organisms respond to rapid change. It can manifest as shifts in behavior, morphology, or phenology (Donelson et al., 2019).

However, plasticity has limits. It is often costly to maintain and may no longer be adaptive if environmental cues become unreliable. Furthermore, plasticity can "shield" genes from natural selection by shifting the mean phenotype closer to the environmental optimum, thereby slowing the rate of genetic evolution (Visser & Gienapp, 2019).

9.2 Evolutionary Rescue and Genetic Adaptation

Evolutionary adaptation occurs across generations through natural selection on heritable traits. For species with short generation times and high genetic diversity, "evolutionary rescue" can occur, where a population evolves rapidly enough to avoid extinction (PNAS, 2020). In some systems, such as wing melanin in certain butterflies, climate change has driven measurable evolutionary shifts in trait means and plasticity levels (Royal Society, 2017). Over longer timescales, plastic responses can become "fixed" through genetic assimilation, transforming a temporary response into a permanent evolutionary feature (Sentis et al., 2018).

10. Adaptive Conservation Management Strategies

The dynamic nature of climate-induced biological change requires a transition from static conservation models to adaptive, cross-scale management frameworks (Climate Adaptation Science Centers, 2025).

10.1 Climate Refugia and Connectivity

Managing for "climate change refugia" areas that remain relatively buffered from regional changes is a primary resistance strategy. These refugia are often created by topographic heterogeneity, such as deep valleys with cold-air pooling, or dense forest canopies that provide thermal buffering (USDA Climate Hubs, 2025). Maintaining "habitat corridors" is equally critical, as they provide the pathways necessary for species to track their shifting niches. Corridors not only facilitate migration but also promote gene flow, reducing the risk of inbreeding in isolated populations (Regeneration.org, 2025).

10.2 The Debate Over Assisted Migration;

As natural dispersal rates prove insufficient for many species, "assisted migration" (or managed relocation) has emerged as a controversial but increasingly necessary tool (PLOS One, 2024).

- **Assisted Population Migration:** Moving seed sources or individuals within the current range to match future climatic projections (Chou et al., 2019).
- **Assisted Range Expansion:** Relocating species to suitable areas just beyond their historical range (Rodríguez-Rodríguez et al., 2017).
- **Assisted Species Migration (Species Rescue):** Moving highly vulnerable species to entirely new habitats far beyond their current range to prevent (Pinsky et al., 2020).
- While critics point to the risks of relocated species becoming invasive or spreading diseases, proponents argue that the "risk of doing nothing" is greater, as sedentary species like redwoods or Joshua trees face certain extirpation without direct intervention (González-Tokman et al., 2020

Table 4: Strategic Framework for Climate-Adaptive Conservation Management

Management Strategy	**Focus**	**Goal**	**Examples**
Resistance	Climate Refugia	Maintain historical structure in buffered areas	Cold-air pools, riparian zones
Resilience	Habitat Quality	Enhance ability to rebound from stressors	Fuel reduction in forests
Connectivity	Wildlife Corridors	Facilitate natural range shifts and gene flow	Mesoamerican Biological Corridor
Transition	Assisted Migration	Facilitate shifts to future suitable habitats	Whitebark pine trials in Canada

11. Impacts on Human Population Geography and Health

The reorganization of the biosphere has profound implications for human societies, affecting demographics, health, and economic stability (IPCC, 2022).

11.1 Displacement and Migration

Climate-induced shifts in ecosystems and the increased frequency of extreme weather events are driving the displacement of human communities. Sea-level rise threatens coastal and island populations, while prolonged droughts and shifting agricultural conditions force rural-to-urban migration as traditional livelihoods collapse (Gotthard et al., 2025). This "climate-induced migration" places significant pressure on the infrastructure and social systems of receiving regions (Allen et al., 2016).

11.2 Health and Economic Risks

Climate change influences public health by altering the distribution of disease vectors, such as mosquitoes that carry West Nile virus or malaria. Furthermore, heatwaves directly increase mortality rates, particularly among vulnerable populations such as the elderly (Legris et al., 2017). The economic cost of these disruptions is staggering; weather and climate disasters in the United States since 1980 have caused over $1.7 trillion in damages and thousands of deaths (PNAS, 2022).

12. Synthesis and Strategic Outlook

The field of climate change biology has evolved from early theoretical models to an empirically grounded discipline that can identify specific drivers of biodiversity loss. The evidence suggests that maximum temperature extremes, physiological bottlenecks in the tropics, and the decoupling of trophic interactions are the primary agents of modern extinctions (Román-Palacios & Wiens, 2020). While phenotypic plasticity and evolutionary adaptation offer pathways for persistence, the unprecedented velocity of contemporary warming suggests that natural processes alone will be insufficient to preserve a significant portion of global biodiversity (Holzmann et al., 2022).

Effective conservation in the twenty-first century must therefore integrate large-scale connectivity with the identification of micro-refugia and the proactive management of range expansions (Chou et al., 2019). The critical bottleneck for many rare and threatened species will occur before 2040, requiring immediate implementation of "climate-smart" conservation strategies (Preprints.org, 2025). Ultimately, the survival of species and the stability of the ecosystems upon which human civilization relies will depend on a combination of rapid greenhouse gas mitigation and an unprecedented level of human stewardship over the Earth's shifting biological landscape (Wernberg et al., 2025).

Conclusion

The accelerating pace of climate change is fundamentally restructuring biological systems, with mounting evidence indicating that extreme climatic events, physiological limits, and disrupted species interactions are central drivers of contemporary biodiversity loss. Species responses are highly variable, shaped by dispersal capacity, niche flexibility, and thermal tolerance, yet many organisms particularly tropical, marine, and range-restricted taxa operate dangerously close to their physiological thresholds. Observed range shifts, phenological mismatches, and trophic cascades demonstrate that climate impacts extend beyond individual species to entire ecosystems, undermining their stability and function. Although phenotypic plasticity and evolutionary adaptation offer important mechanisms for persistence, they are unlikely to offset the magnitude and speed of ongoing climate change without human intervention. Conservation strategies must therefore move beyond static protection frameworks toward dynamic, climate-adaptive management that prioritizes habitat connectivity, identification of micro-refugia, and, where necessary, assisted migration. The critical window for preventing irreversible biodiversity loss is rapidly narrowing, with decisive action required well before mid-century. Sustaining global biodiversity and the ecosystem services upon which human societies depend will ultimately hinge on the dual commitment to aggressive climate mitigation and informed, forward-looking conservation stewardship.

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