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Effects of climate change on wildlife distribution, habitat suitability, population dynamics, and species survival: A synthesis of current evidence

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Abstract

Climate change is now a dominant force reshaping the geographic distribution, habitat suitability, demographic performance, and long-term survival prospects of wild species across terrestrial, freshwater, and marine realms. This review synthesises peer-reviewed evidence on four interlinked dimensions of ecological response: (i) documented shifts in species ranges toward higher latitudes, elevations, and depths; (ii) the use and limitations of correlative habitat suitability and species distribution models for projecting future range change; (iii) climate-driven alterations to population dynamics, including phenological mismatch, demographic decline, and the compounding effects of extreme events and habitat fragmentation; and (iv) quantitative assessments of extinction risk, illustrated through case evidence from polar, alpine, and coral-reef systems. Across taxa, range shifts are broadly consistent with a warming climate but vary substantially with species traits, dispersal capacity, and landscape connectivity, producing a widening “climate debt” between the pace of climatic change and the realised responses of many species. Population-level consequences are frequently mediated by interacting, non-climatic stressors such as habitat fragmentation and land-use change, complicating attribution. Meta-analytic evidence indicates that a meaningful proportion of assessed species face elevated extinction risk under continued warming, with risk accelerating non-linearly at higher temperature thresholds. The review identifies persistent evidence gaps—particularly for tropical, freshwater, and range-interior populations—and outlines adaptation-oriented conservation responses, including climate-informed protected-area design and landscape connectivity. No new empirical data were generated; all quantitative figures cited are drawn from previously published sources.

Keywords: Climate change, species distribution shift, habitat suitability modelling, population dynamics, extinction risk, phenological mismatch, wildlife conservation

Introduction

Anthropogenic climate change has moved from a projected future risk to a measurable, ongoing driver of ecological change. Rising global mean temperatures, shifting precipitation regimes, ocean warming and acidification, and an increasing frequency of extreme climatic events are altering the physical templates within which wild populations live, reproduce, and interact (IPCC, 2022). Because most species' physiology, phenology, and behaviour are tuned to historical climatic conditions, even modest departures from these conditions can propagate through individual performance to population dynamics and, ultimately, to the persistence of species (Parmesan & Yohe, 2003; Parmesan, 2006) ^[9, 10].

Four interlinked lines of evidence are commonly used to characterise these effects. First, long-term monitoring and resurvey studies document directional shifts in species' geographic ranges, generally poleward in latitude and upward in elevation, as organisms track shifting climatic envelopes (Chen *et al.*, 2011; Parmesan & Yohe, 2003) ^[4, 10]. Second, correlative habitat suitability models—commonly termed species distribution models (SDMs) or ecological niche models—are widely used to project how the spatial extent of climatically suitable habitat is likely to change under alternative emissions scenarios, informing conservation planning even though such models carry important structural limitations (MacLean & Beissinger, 2017) ^[8]. Third, a growing body of demographic and phenological research shows that climate change affects not only where species occur but how well their populations perform where they do occur, through mechanisms such as phenological mismatch between consumers and resources, altered survival and reproduction, and interactions with non-climatic stressors such as habitat

fragmentation (Renner & Zohner, 2018) ^[17]. Fourth, quantitative extinction-risk assessments attempt to translate these mechanisms into estimates of species-level vulnerability under continued warming (Urban, 2015) ^[20]. These four dimensions—distribution, habitat suitability, population dynamics, and survival—are conceptually and empirically linked: changes in climatic suitability reshape the geography of populations, which in turn determines local demographic performance, cumulative population trends, and ultimately the probability of persistence or extinction. However, the strength and directness of these links vary considerably across taxa, biomes, and spatial scales, and are frequently obscured by co-occurring, non-climatic pressures such as land-use change, overexploitation, and pollution (Living Planet Index, WWF & ZSL, 2024). This review synthesises current, predominantly post-2010 peer-reviewed literature across these four dimensions, with particular attention to the mechanisms connecting them, the quality and limitations of the underlying evidence base, and the implications for conservation practice. Consistent with an evidence-based, anti-fabrication approach to synthesis, no new empirical data, statistical results, or species assessments are generated here; all quantitative claims are attributed to their original published sources.

Conceptual Framework

Figure 1 summarises, in schematic form, the causal pathway typically invoked in the literature linking climate drivers to species-level outcomes. Climate drivers (warming, altered precipitation, ocean warming and acidification, and extreme events) generate proximate ecological responses—range shifts, phenological shifts, and physiological stress—that jointly alter the climatic suitability of habitat for a given species. Changes in habitat suitability then propagate to population dynamics through altered survival, fecundity, recruitment, and connectivity, with cumulative consequences for species persistence or extinction risk. This pathway is moderated throughout by species traits (dispersal ability, thermal tolerance, generation time), by adaptive capacity (phenotypic plasticity and the potential for evolutionary response), and by non-climatic stressors such as land-use change and habitat fragmentation, which can either buffer or exacerbate climate impacts (Renner & Zohner, 2018; Beever *et al.*, 2011) ^[2, 17]. This framework organises the subsequent sections of the review.

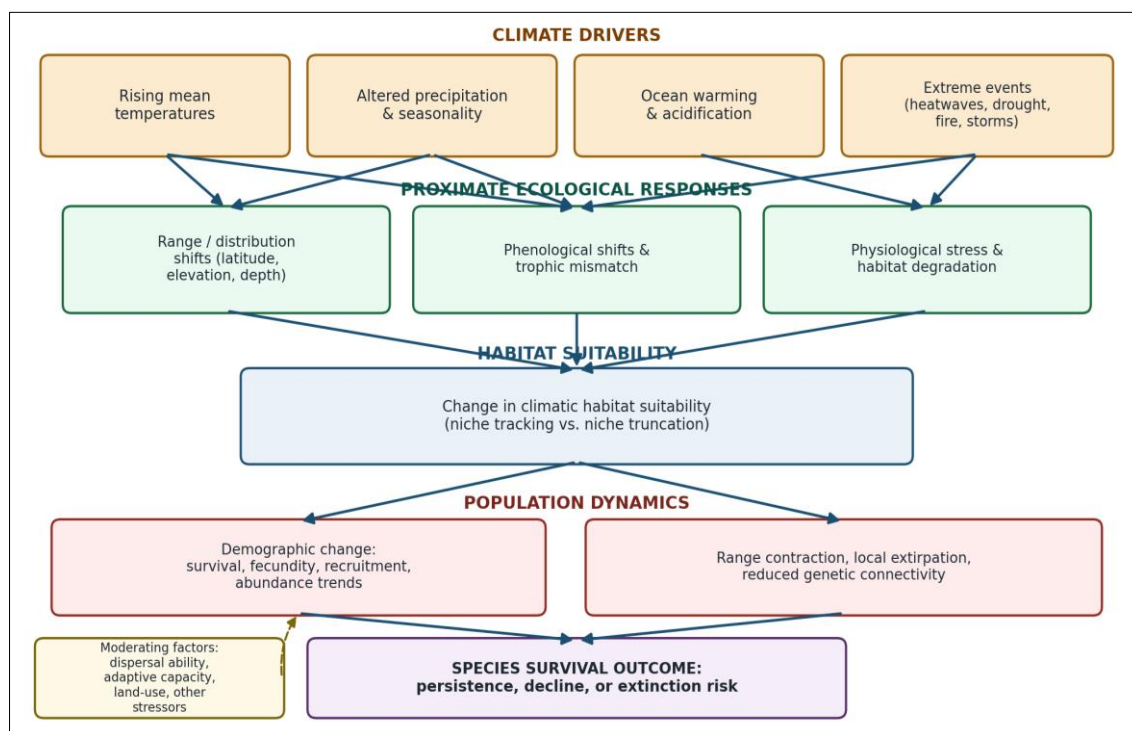


Fig 1: Conceptual framework linking climate change drivers to wildlife distribution, habitat suitability, population dynamics and survival outcomes. Schematic synthesis of mechanisms described in the cited literature; not derived from a specific dataset.

Climate-Driven Shifts in Species Distribution

1. Terrestrial range shifts

The observation that many terrestrial species are shifting their ranges toward higher latitudes and elevations is among the most consistently replicated findings in climate ecology. An influential global meta-analysis estimated that terrestrial species' distributions have shifted to higher elevations at a median rate of approximately 11.0 metres per decade and to higher latitudes at a median rate of approximately 16.9 kilometres per decade, rates roughly two to three times faster than earlier estimates (Chen *et al.*, 2011) ^[4]. These shifts are broadly proportional to the magnitude of local warming, with the largest range displacements occurring in regions experiencing the greatest temperature increases. An earlier, widely cited synthesis similarly found a globally coherent “fingerprint” of climate change across natural systems, with the great majority of studies reporting range or phenological shifts in the direction expected under warming (Parmesan & Yohe, 2003) ^[10].

Not all species shift at the same rate, however. A comprehensive trait-based meta-analysis spanning more than fifty studies and over 11,000 species-level responses found that range shifts were consistently associated with species' habitat breadth and historical range position, but that commonly hypothesised predictors such as body size, fecundity, and diet breadth showed

inconsistent or non-significant effects across studies (MacLean & Beissinger, 2017)^[8]. This heterogeneity indicates that simple trait-based rules of thumb are insufficient to predict which species will track climate change successfully and which will lag behind, reinforcing the need for species- and context-specific assessment rather than generalised extrapolation.

2. Marine and freshwater shifts

Marine species have, on average, shifted their distributions considerably faster than terrestrial species, reflecting the greater velocity of climate change in the ocean relative to land (Burrows *et al.*, 2011; Poloczanska *et al.*, 2013)^[3, 13]. Leading-edge range boundaries of marine taxa have advanced by tens of kilometres per decade, generally poleward, alongside measurable advances in spring phenology (Poloczanska *et al.*, 2016)^[14]. The concept of climate velocity—the rate and direction at which isotherms move across a landscape or seascape—has proven useful for explaining variation in the pace and direction of range shifts across marine taxa and regions, with species tracking local climate velocities more closely in the ocean than has typically been observed on land (Pinsky *et al.*, 2013; García Molinos *et al.*, 2016)^[5, 12]. Importantly, rapid range-shift velocity is not necessarily beneficial: recent evidence indicates that marine fish populations undergoing the fastest poleward shifts have also experienced substantial concurrent declines in local abundance, suggesting that rapid geographic tracking does not guarantee demographic stability.

3. Traits, constraints, and range-shift lag

A recurring theme across both terrestrial and marine evidence is that the pace of climate change frequently outstrips the capacity of many species to track shifting climatic conditions, producing a lag commonly described as “climate debt.” This lag is illustrated schematically in Figure 2, which contrasts the velocity of climatically suitable conditions with the range-shift trajectories of species differing in dispersal capacity and habitat specialisation. Species with greater dispersal ability, broader ecological tolerance, and higher reproductive rates are generally better positioned to colonise newly suitable habitat, whereas habitat specialists, poor dispersers, and species confined by landscape barriers or fragmentation tend to lag further behind shifting climatic conditions (Sunday *et al.*, 2015; MacLean & Beissinger, 2017)^[8, 19]. Species traits interact with landscape context: habitat fragmentation, in particular, can sever the connectivity pathways that would otherwise allow species to track shifting climate envelopes, compounding the mismatch between climatic and realised distributions (Pecl *et al.*, 2017)^[11].

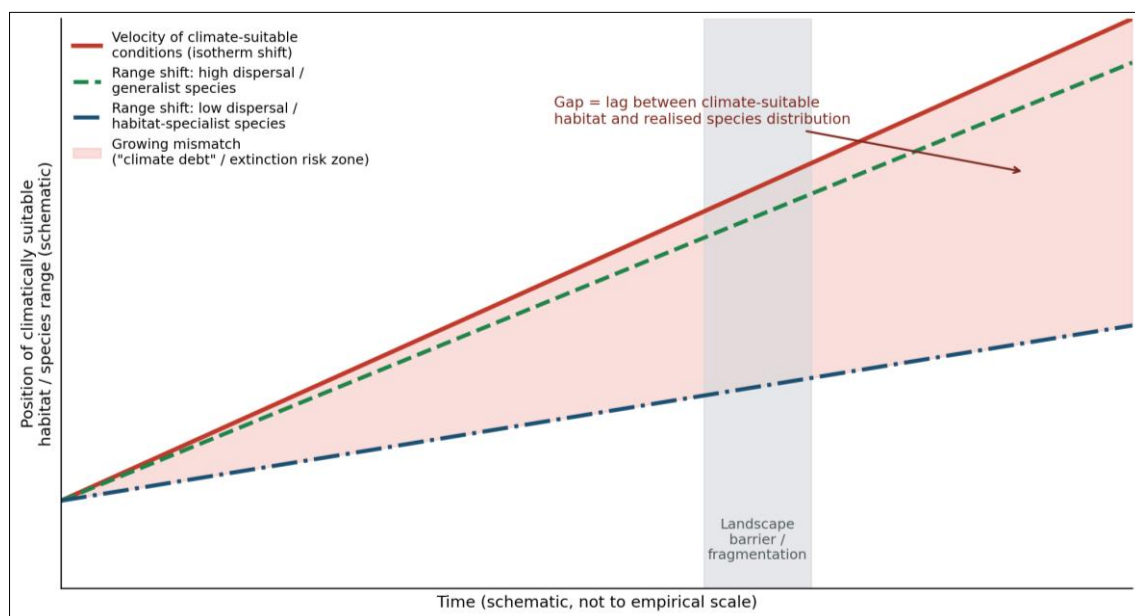


Fig 2: Schematic illustration of climate-velocity tracking and the resulting range-shift lag between climatically suitable habitat and species with differing dispersal capacity. Conceptual diagram constructed to illustrate mechanisms described in the cited literature; axes are illustrative and not derived from a specific empirical dataset.

Habitat Suitability Modelling Under Climate Change

Correlative species distribution models (SDMs), also termed ecological or climatic niche models, are the principal tool used to project how climatically suitable habitat for a given species is likely to change under future climate scenarios. These models statistically relate current species occurrence records to a set of environmental predictors (commonly bioclimatic variables describing temperature and precipitation regimes) and project the resulting relationship onto future climate scenarios, typically Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs), to estimate future habitat suitability (MacLean & Beissinger, 2017)^[8]. Such models have been applied across an extremely broad range of taxa and regions, frequently projecting substantial contraction, fragmentation, or poleward/upward relocation of climatically suitable area by the mid- to late twenty-first century, with the magnitude of projected change generally increasing under higher-emissions scenarios. Despite their widespread use, SDMs carry well-documented limitations that bear directly on the credibility of habitat suitability projections. Correlative models describe realised climatic associations rather than mechanistic physiological tolerances, and may therefore misrepresent a species' fundamental niche where current distributions are constrained by biotic interactions, dispersal limitation, or historical contingency rather than climate alone. Model projections can also diverge substantially depending on

the choice of algorithm, the selection of environmental predictors, and the treatment of non-climatic factors such as land-use change and dispersal constraints, and different modelling approaches applied to the same species can generate materially different range-change forecasts. Studies that combine climatic and non-climatic (biotic, land-use, and dispersal) predictors within a single modelling framework tend to yield more ecologically plausible and more conservative projections than purely climate-based models, underscoring that habitat suitability is a necessary but not sufficient condition for species persistence.

A further caveat concerns the interpretation of projected habitat gain. Several SDM studies project that a subset of species will gain climatically suitable area at higher latitudes or elevations even as they lose suitable area within their current range; however, the realisation of such gains depends on dispersal capacity, the presence of suitable non-climatic habitat conditions (soils, prey availability, vegetation structure) at the newly suitable location, and the absence of landscape barriers—conditions that are frequently not met in practice. As a result, projected future habitat suitability should be interpreted as an upper bound on the area a species could occupy under idealised dispersal, rather than a forecast of realised future distribution.

Population Dynamics: Phenology, Demography, and Compounding Stressors

1. Phenological mismatch and trophic asynchrony

Beyond spatial redistribution, climate change alters the timing of key life-history events—breeding, migration, emergence, and flowering—often at different rates across interacting species, a phenomenon termed phenological mismatch or trophic asynchrony (Renner & Zohner, 2018) ^[17]. Because many consumer species depend on the seasonal availability of specific resources, differential phenological responses among interacting species can decouple consumers from their food supply. Evidence for such mismatch is clearest in high-latitude antagonistic interactions; for example, geese in Arctic breeding grounds have been shown to only partially adjust their breeding phenology to track the advancing peak in food-plant nutritional quality, producing mismatches associated with reduced offspring growth (Renner & Zohner, 2018) ^[17]. In a large-herbivore case study spanning a wide elevational gradient in Switzerland, roe deer exhibited limited phenotypic plasticity in parturition timing relative to the advancing phenology of forage plants, indicating that trophic mismatch can arise even in mobile, generalist herbivores with access to elevational climate gradients (Rehner *et al.*, 2020) ^[16]. At the population level, studies of long-term avian datasets indicate that species advancing their breeding phenology the least relative to shifts in prey availability tend to show the most negative population trends, providing a mechanistic link between phenological mismatch and demographic decline (Renner & Zohner, 2018) ^[17].

2. Extreme events and compounding, non-climatic stressors

Population-level responses to climate change are rarely attributable to gradual warming alone; extreme events (heatwaves, droughts, storms, and wildfire) and their interaction with existing non-climatic stressors frequently drive the most abrupt and consequential population changes. Habitat fragmentation, in particular, interacts with climate change in two directions: fragmentation itself is increasingly driven by climate-related disturbances such as wildfire and storm damage, while pre-existing fragmentation constrains the ability of populations to track shifting climate envelopes or to buffer the demographic impact of extreme events through movement or immigration. Historical analyses of mammalian local extinctions indicate that both human disturbance and extreme climatic departures are independently associated with local extinction risk, complicating efforts to attribute population decline to a single dominant driver. This attribution challenge is compounded at the global scale: the Living Planet Index, which tracks trends in nearly 35,000 monitored vertebrate populations, reported an average decline of 73% between 1970 and 2020, with habitat loss and degradation identified as the most commonly reported threat, followed by overexploitation, invasive species and disease, and climate change acting as an additional and increasingly important compounding pressure rather than the sole driver (WWF & ZSL, 2024).

Species Survival and Extinction Risk: Evidence and Case Illustrations

The most widely cited quantitative synthesis of climate-related extinction risk combined results from more than 130 published studies encompassing a broad range of taxa, geographic regions, and modelling approaches. This meta-analysis estimated that, on average, approximately one in six species (around 16%) could face extinction if warming proceeds along a trajectory consistent with policy targets in place at the time of the analysis, with predicted extinction risk accelerating disproportionately at higher levels of warming and with the greatest projected risk concentrated in South America, Australia, and New Zealand (Urban, 2015) ^[20]. A subsequent, substantially larger synthesis incorporating several hundred studies and millions of individual model projections has extended this quantitative assessment, reinforcing the general finding that extinction risk rises non-linearly with global temperature rise, while also highlighting persistent uncertainty in risk estimates across taxa and regions.

Species- and system-specific case evidence illustrates how the mechanisms described above translate into measurable survival outcomes. In the Arctic, the polar bear (*Ursus maritimus*) depends on sea ice as a platform for hunting seals, and the loss of Arctic sea ice is considered the primary threat to the species throughout its range. A formal IUCN Red List assessment combining sea-ice projections with demographic modelling estimated a 0.71 probability that the global polar bear population will decline by more than 30% over three generations (35–41 years), a result consistent with the species' current Vulnerable status; the same assessment estimated a much lower probability (0.07) of a decline exceeding 50% (Regehr *et al.*, 2016) ^[15]. Subsequent IUCN Polar Bear Specialist Group assessments confirm that responses vary regionally, with several subpopulations (e.g., Southern Beaufort Sea, Western and Southern Hudson Bay) in documented decline, while a small number of high-Arctic subpopulations have shown temporary stability associated with local, transitional increases in prey access as multi-year ice breaks up.

In alpine systems, the American pika (*Ochotona princeps*), a small, cold-adapted lagomorph with narrow thermal tolerance, has experienced documented local extinctions across parts of its range in the western United States, with surveys attributing an increasing share of these losses to direct thermal stress rather than the habitat loss, exploitation, or invasive-species pressures

that more typically drive vertebrate declines (Beever *et al.*, 2010, 2011)^[1, 2]. Regional resurveys have also documented upslope retraction of the species' minimum elevation of occupancy, consistent with the range-shift-lag dynamic depicted schematically in Figure 2, and separate work has documented complete local extirpation of the species across large contiguous areas of California's Sierra Nevada, illustrating that management options for narrowly adapted, poorly dispersing alpine specialists are often limited.

In marine systems, reef-building corals provide a further illustration of climate-driven survival risk operating through acute physiological stress rather than gradual range shift. Repeated large-scale coral bleaching events, driven by anomalously warm sea-surface temperatures, have caused substantial coral mortality in multiple ocean basins over the past three decades, with modelled coral-population responses indicating that recovery between successive bleaching events becomes increasingly difficult to sustain population structure as the frequency of thermal-stress events increases (Riegl, 2008)^[18]. Because reef-building corals are long-lived, slow-growing, and provide the structural habitat underpinning reef biodiversity, climate-driven coral mortality has cascading implications for the many reef-associated species that depend on coral habitat structure, illustrating how climate impacts on a single foundation species can propagate to broader community- and ecosystem-level survival outcomes.

Research Gaps

Several gaps recur across the literature reviewed here. First, geographic and taxonomic coverage remains uneven: range-shift and extinction-risk evidence is disproportionately drawn from well-studied temperate terrestrial taxa (birds, butterflies) and marine fish, while tropical, freshwater, and many invertebrate and plant taxa remain comparatively understudied despite housing a large share of global biodiversity and, in the case of freshwater systems, some of the highest documented rates of local extirpation. Second, most range-shift studies characterise movement at range margins (leading and trailing edges) rather than within the range interior, leaving population-level demographic consequences in range-core areas comparatively poorly resolved. Third, the attribution of population decline to climate change specifically, as distinct from co-occurring stressors such as land-use change, overexploitation, and pollution, remains methodologically difficult, and most studies are not designed to formally partition these contributions. Fourth, habitat suitability projections are rarely validated against subsequently observed range change, limiting confidence in long-horizon (multi-decadal) SDM forecasts. Finally, evidence on evolutionary and adaptive-capacity responses (genetic adaptation, phenotypic plasticity) remains sparse relative to the volume of correlative distribution and demographic evidence, constraining the ability to project species-specific resilience under continued warming.

Conservation and Management Implications

The evidence synthesised here supports several adaptation-oriented conservation responses that are increasingly reflected in international guidance. The IPCC's Sixth Assessment Report identifies well-designed protected-area networks, restoration of degraded habitat, and the maintenance or creation of landscape connectivity (ecological corridors) as high-confidence strategies for increasing the resilience of biodiversity to climate change (IPCC, 2022). Because static protected-area boundaries can become mismatched with dynamically shifting species distributions, several jurisdictions have begun designing protected-area networks and corridor systems explicitly to accommodate projected climate-driven range shifts, prioritising connectivity between current protected habitat and climatically projected future refugia (Krosby *et al.*, 2010)^[7]. For a small number of severely dispersal-limited or otherwise immobile species, managed relocation (assisted migration) has been proposed and, in limited cases, implemented, though this approach remains constrained by cost, regulatory complexity, and ecological risk to recipient ecosystems, and is generally regarded as a last-resort option rather than a general-purpose strategy (IPCC, 2022).

Because population declines are frequently driven by the interaction of climate change with other stressors, conservation strategies that reduce non-climatic pressures—curbing habitat loss and fragmentation, regulating overexploitation, and controlling invasive species—are likely to increase the resilience of populations to a given level of climatic change even where climate change itself cannot be locally mitigated. This is consistent with the Living Planet Index finding that habitat loss and degradation remain the most frequently reported proximate threat to monitored vertebrate populations globally, with climate change acting as a compounding rather than singular driver in most documented cases (WWF & ZSL, 2024). At the same time, the case evidence reviewed here (polar bears, alpine specialists, reef-building corals) indicates that for species whose persistence depends on a specific, climate-sensitive physical substrate—sea ice, high-elevation cold refugia, or narrow thermal tolerance windows for symbiosis—the primary and most direct point of intervention remains the mitigation of global greenhouse gas emissions, since local management actions alone cannot restore the underlying climatic conditions on which these species depend.

Limitations of This Synthesis

This review has several limitations that should be considered when interpreting its conclusions. It is a narrative synthesis of secondary literature rather than a systematic review or meta-analysis, and does not follow a pre-registered search protocol (e.g., PRISMA); consequently, the coverage of evidence, while intended to be representative of major themes and landmark findings, is not guaranteed to be exhaustive, and reference selection prioritised evidence quality, relevance, and landmark status within a bounded reference list rather than complete topical coverage. All quantitative estimates reported here (range-shift rates, extinction-risk probabilities, population-decline percentages) are drawn directly from the cited primary and secondary sources; no new statistical analysis, modelling, or data collection was undertaken as part of this synthesis, and no claims are made regarding findings beyond what the cited sources report. Because the underlying primary literature itself varies in geographic,

taxonomic, and methodological scope (Section 7), the conclusions drawn here inherit those same coverage gaps and should not be over-generalised to taxa or regions for which direct evidence was not identified.

Conclusion

Climate change is reshaping wildlife distribution, habitat suitability, population dynamics, and survival prospects through an interconnected set of mechanisms that operate across terrestrial, freshwater, and marine systems alike. Range shifts toward higher latitudes, elevations, and depths are well documented and broadly track the magnitude of local warming, but the pace and completeness of these shifts vary substantially with species traits and landscape connectivity, producing a growing lag between climatically suitable habitat and realised species distributions for many taxa. Habitat suitability models provide a useful, if imperfect, tool for anticipating the direction and rough magnitude of future range change, but their projections represent potential rather than guaranteed future distributions. Population-level consequences of climate change are frequently mediated by phenological mismatch and are compounded by interacting, non-climatic stressors, complicating simple attribution of observed declines to climate change alone. Quantitative extinction-risk assessments indicate that a substantial proportion of species face elevated risk under continued warming, with case evidence from polar, alpine, and coral-reef systems illustrating how these risks are already materialising for climate-sensitive species. Addressing these risks will require both climate-informed conservation planning—protected-area redesign, connectivity, and, in limited cases, managed relocation—and continued mitigation of the underlying drivers of global warming, alongside expanded research attention to the taxonomic, geographic, and mechanistic gaps identified in this review.

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