Check for updates

Animal Population Patterns in Uncertain Climates: A Systematic Review

Ambreen Ilyas

School of Biological Sciences, University of the Punjab, Lahore, Pakistan

Correspondence to: Ambreen Ilyas, ambreen2.phd.sbs@pu.edu.pk

Additional material is published online only. To view please visit the journal online.

Cite this as: Ilyas A. Animal Population Patterns in Uncertain Climates: A Systematic Review. Premier Journal of Environmental Science 2026;6:100023

DOI: https://doi.org/10.70389/PJES.100023

Peer Review
Received: 3 January 2026
Revised: 29 January 2026
Accepted: 3 February 2026
Version accepted: 6
Published: 20 February 2026

Ethical approval: N/a
Consent: N/a
Funding: No industry funding
Conflicts of interest: N/a
Author contribution: Ambreen Ilyas – Conceptualization, Writing – original draft, review and editing
Guarantor: Ambreen Ilyas

ABSTRACT

Climate change is increasingly characterized by heightened variability, unpredictability, and extreme events, presenting profound challenges for animal populations across global ecosystems. This review synthesizes current scientific literature to examine how climatic uncertainty, beyond changes in mean temperature, reshapes animal population patterns, including abundance, distribution, migration, and long-term persistence. Drawing on evidence from terrestrial, freshwater, and marine systems, we highlight how fluctuations in temperature and precipitation disrupt demographic processes such as survival, reproduction, and recruitment, often increasing extinction risk in species with narrow physiological tolerances or specialized ecological niches. Particular attention is given to migratory species, where climate-driven shifts in phenology across breeding and non-breeding regions generate trophic mismatches and weaken population connectivity. The review further explores how extreme climatic events can restructure age composition and density-dependent dynamics, producing non-linear and sometimes counterintuitive population responses. Importantly, climate uncertainty rarely acts in isolation; it interacts synergistically with habitat fragmentation, land-use change, and emerging disease pressures, compounding stress on wildlife populations. We also assess the growing evidence that climate variability accelerates the erosion of genetic diversity, thereby constraining adaptive capacity and evolutionary resilience. By comparing theoretical models with empirical observations, this review underscores the limitations of population assessments that focus solely on average climatic trends and neglect variability and extremes. We conclude by identifying critical knowledge gaps and outlining future research priorities, including the integration of climate variability into population models, long-term monitoring, and adaptive conservation planning. Understanding animal population patterns under uncertain climates is essential for anticipating biodiversity trajectories and informing resilient management strategies in an era of accelerating environmental change.

Keywords: Phenological mismatch, Migration connectivity, Extreme climatic Events, Genetic diversity erosion, Climate-induced range shifts

Introduction

Climate change has emerged as a foremost driver of biodiversity loss, profoundly influencing animal population dynamics through not only shifts in average temperature and precipitation but also rising climatic variability and extreme events. Climatic uncertainty characterized by unpredictable fluctuations, heatwaves, cold snaps, and altered seasonal patterns plays a critical role in shaping demographic processes such as survival, reproduction, migration, and extinction risk across taxa and habitats.[1,2] Traditional research that emphasizes mean climatic trends often overlooks these temporal irregularities, which can generate idiosyncratic population responses among species with differing ecological strategies.[3,4]

Recent long-term studies demonstrate that climatic variability drives individualistic and sporadic population fluctuations, with some species experiencing dramatic "crashes" or "explosions" in abundance unrelated to long-term averages, reflecting heterogeneous responses to short-term climate anomalies.[4] Temperature extremes such as cold snaps and heatwaves have been shown to reduce reproductive success and fitness in numerous bird species, further illustrating how variability, rather than warming alone, influences population trajectories.[5] Additionally, broad meta-analyses reveal that responses to weather anomalies are highly variable even within mammal populations, underscoring the complexity of climate–population interactions.[6]

Climate change also affects movement and distribution. Altered weather patterns have already modified migration timing and routes in birds and large mammals, with half of studied species shifting ranges toward higher latitudes or elevations to track suitable conditions.[7,8] These shifts are not consistent across species or regions, with empirical evidence showing that expected range shifts often do not align with theoretical predictions.[9]

Compounding these dynamics, genetic diversity is declining in many animal populations, reducing adaptive capacity and resilience to ongoing environmental change.[10,11] Extreme weather events and climatic variability can accelerate genetic drift and erode genetic variation, increasing extinction risk in vulnerable populations.[12] Conservation science highlights the interplay between climate variation and other anthropogenic pressures, such as habitat fragmentation, land-use change, and disease dynamics, all of which further stress wildlife populations.[13] In mountain ecosystems, rising temperatures and altered moisture regimes have been linked to shifts in seasonal movements of large mammals, directly affecting population stability.[14] Moreover, climatic impacts extend to human-dominated systems; livestock dynamics and breed distributions also fluctuate in response to climatic variability, evidencing that climate impacts transcend wild populations alone.[15]

These complex, multi-scale interactions underscore the urgency of integrating climatic uncertainty into models of animal population dynamics to better

Provenance and peer-review: Unsolicited and externally peer-reviewed

Data availability statement: N/a

predict biodiversity trajectories and inform adaptive conservation strategies.

This review advances prior syntheses by explicitly integrating climatic variability and extremes with demographic, migratory, and genetic processes, and by translating evidence into a decision-support framework for conservation planning under uncertainty. Accordingly, this manuscript is reported as a systematic review conducted and documented in accordance with PRISMA 2020 standards.

Methodology

Study Selection and PRISMA Flow

A systematic literature search identified 4,482 records from Web of Science, Scopus, PubMed, and Google Scholar (Figure 1). Following removal of 812 duplicate records, 2,670 unique records were screened at the title–abstract level. Of these, 2,210 records were excluded for failing to meet inclusion criteria, most commonly due to non-animal focus, absence of population-level outcomes, lack of explicit climate drivers, theoretical or modeling-only approaches, narrative or opinion-based formats, or exclusive focus on long-term mean warming rather than climatic variability or extremes.

The remaining 460 articles were retrieved and assessed at full text for eligibility. At this stage, 320 studies were excluded for predefined reasons, including focus on mean climate trends only, absence of empirical population metrics, use of grey or non-peer-reviewed sources, plant-only or inseparable mixed systems, insufficient methodological detail, or duplication of datasets.

In total, 140 peer-reviewed empirical studies met all eligibility criteria and were included in the qualitative synthesis and quantitative summaries. A complete PRISMA-compliant audit trail, including detailed exclusion reasons at each screening stage and the full list of included studies, is provided in Supplementary File S4.

Title–abstract and full-text screening was conducted by the author using a structured decision protocol (Supplementary Table S2). To assess screening reliability, a second trained researcher independently reviewed a randomly selected 15% subset of records at both screening stages. Inter-rater agreement was high (Cohen's $\kappa = 0.82$). Discrepancies were resolved by discussion, and decision rules were finalized prior to completion of screening.

Literature Search Strategy

A systematic literature search was conducted in accordance with PRISMA 2020 guidelines. Four electronic databases—Web of Science, Scopus, PubMed, and Google Scholar—were searched from inception to December 2025. Search strings combined terms related to animal populations, climate variability, and climatic extremes using Boolean operators (e.g., animal population AND climate variability OR extreme events). Database-specific filters were applied to restrict results to peer-reviewed journal articles published in English. Full search strings for each database are provided in Supplementary File S1.

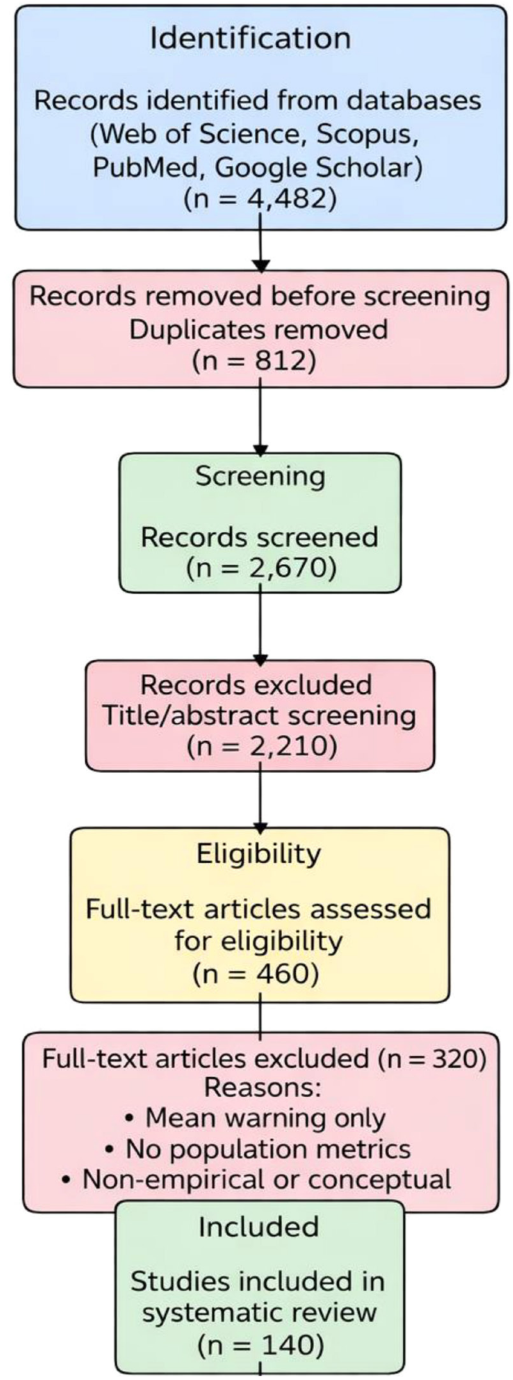

Fig 1 | PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the systematic review. The final synthesis includes 140 peer-reviewed empirical studies examining animal population responses to climate variability and climatic extremes

Eligibility Criteria

Only peer-reviewed empirical studies examining animal population-level responses to climate variability and/or climatic extremes were eligible for inclusion. Studies focusing exclusively on plants, long-term mean climate trends, conceptual frameworks, or non-empirical sources (e.g., reviews, commentaries, news articles) were excluded.

Climate variability was defined as short- to medium-term deviations from long-term climatic means (e.g., interannual or seasonal anomalies), while climatic extremes were defined as statistically rare events exceeding the 90th or 10th percentile of historical distributions, including heatwaves, droughts, floods, and extreme precipitation.

Screening and Study Selection

All records were imported into a reference manager, and 812 duplicate records were removed prior to screening. The remaining 2,670 unique records underwent title–abstract screening conducted by the first author. To ensure screening reliability, a random 15% subset of records was independently screened by a second reviewer. Inter-reviewer agreement was high (Cohen's $\kappa = 0.82$), indicating substantial agreement.

Records were excluded at this stage if they: (i) did not focus on animal taxa, (ii) lacked population-level outcomes, (iii) did not treat climate as a primary driver, (iv) were purely theoretical or modeling-based without empirical validation, (v) were narrative reviews or opinion pieces, or (vi) addressed only long-term mean climate trends without reference to variability or extremes.

Following title–abstract screening, 460 articles were assessed at full text for eligibility.

Full-Text Eligibility and Inclusion Criteria

Full-text articles were evaluated against predefined eligibility criteria. Studies were excluded if they: (i) examined only mean climate trends, (ii) lacked empirical population-level metrics, (iii) were grey literature or otherwise non–peer-reviewed, (iv) focused exclusively on plant systems or inseparable plant–animal assemblages, (v) provided insufficient methodological detail to support inference, or (vi) represented duplicate datasets.

Following full-text assessment, 320 studies were excluded, resulting in 140 peer-reviewed empirical studies included in the final qualitative synthesis and quantitative summaries. A complete audit trail of study selection, including exclusion reasons at each stage and the full list of included studies, is provided in Supplementary File S4.

Operational Definitions of Climate Variability and Extremes

For inclusion, studies were required to explicitly address climate variability and/or climatic extremes, defined as deviations from long-term climatic means operating over intra-annual, interannual, or seasonal timescales. Climate variability included measures such as variance, anomalies, or coefficients of variation in temperature or precipitation. Climatic extremes included discrete events (e.g., heatwaves, droughts, extreme precipitation, cold spells) defined using study-specific thresholds (e.g., percentile-based or exceedance criteria). Where heterogeneous metrics were reported, outcomes were harmonized into proportional summaries based on the direction and nature of population responses.

Quality Appraisal and Sensitivity Analysis

Study quality was assessed using a predefined rubric evaluating statistical rigor, temporal depth, causal inference, and reporting transparency (Supplementary Table S3). Each study was assigned a categorical quality score (high, medium, or low). Quality scores were used to inform narrative weighting, and sensitivity analyses were conducted to evaluate whether proportional outcomes were robust to exclusion of lower-quality studies.

Study-quality scores informed interpretive weighting in the narrative synthesis, with greater emphasis placed on long-term, methodologically robust studies. Numerical proportions were not reweighted by quality score to avoid introducing subjectivity; however, sensitivity to study quality is discussed qualitatively in the Results and Discussion.

Google Scholar searches were conducted using predefined keyword strings, with screening limited to the first 300 results per query, consistent with established systematic review practice. Screening logs, data extraction sheets, PRISMA files, and quality appraisal scores are deposited in an open repository (OSF) with Project DOI https://doi.org/10.17605/OSF.IO/S8QMZ.

Supplementary File S4 provides a PRISMA-compliant audit trail documenting study exclusion and inclusion across all screening stages. Supplementary Tables S4A–C detail records excluded prior to screening, during title–abstract screening, and at full-text assessment, with explicit reasons aligned to PRISMA categories. Supplementary Table S4D lists all 140 peer-reviewed empirical studies included in the qualitative and quantitative synthesis.

Statistical rigor: Appropriateness of analytical methods and treatment of confounding factors

Temporal depth and replication: Length and continuity of population time series

Causal inference: Strength of mechanistic links between climatic drivers and population responses

Reporting transparency: Clarity of methods, uncertainty estimates, and data availability

Studies were assigned quality scores, which informed evidence weighting during synthesis. Detailed quality assessment criteria and study-level scores are provided in Supplementary Table S3.

Evidence Synthesis

Given the heterogeneity of taxa, climatic drivers, and response variables, a multi-tiered synthesis approach was applied.

Narrative Synthesis

Qualitative synthesis was used to identify recurring patterns across taxa and ecosystems, including directional responses to climatic variability, non-linear effects, and life-history mediators of vulnerability.

Quantitative Integration

Where available, effect size estimates from meta-analyses and long-term empirical studies were integrated to assess the magnitude and consistency of climate impacts on demographic rates. For proportional summaries, each included peer-reviewed empirical study constituted a single analytical unit (Supplementary Table S4). Outcomes were categorized as negative (e.g., reduced survival, fecundity, or recruitment), neutral/mixed, or positive responses to climatic variability or extremes. When multiple populations or taxa were reported within a study, each was recorded separately but weighted equally. Proportions are reported with exact binomial 95% confidence intervals and stratified by major taxonomic group, ecological realm (terrestrial, freshwater, marine), and dominant climate driver. Study-quality scores (Supplementary Table S3) informed narrative interpretation but were not used to weight numerical proportions.

Conceptual Integration

Synthesized evidence was used to develop mechanistic frameworks linking climate variability, life-history traits, ecological interactions, and population outcomes, supporting interpretation and hypothesis generation.

Limitations and Scope

This review acknowledges potential limitations, including geographic and taxonomic biases in the available literature, variability in climatic measurement approaches, and underrepresentation of long-term datasets in some regions. Nonetheless, the structured methodology, transparent criteria, and integration of multiple evidence streams provide a robust foundation for assessing population responses to climatic uncertainty.

Given the heterogeneity of study designs, taxa, climate drivers, and reported response metrics, formal meta-analysis was not feasible for all response variables. Instead, structured vote-counting was employed, supplemented by proportional summaries with binomial confidence intervals where applicable. Results are stratified by taxonomic group, ecological realm, and dominant climate driver. Study quality scores informed interpretive weighting but not numerical aggregation.

The synthesized evidence base is geographically and taxonomically uneven, with strong representation from temperate terrestrial vertebrates but comparatively limited coverage of tropical systems, freshwater taxa, and herpetofauna (Supplementary Table S4D). These gaps likely reflect broader disparities in long-term ecological monitoring and may bias inference toward well-studied regions and taxa, underscoring the need for expanded research in underrepresented systems.

Transparency and Supplementary Materials

To ensure reproducibility and transparency, supplementary materials include:

Supplementary Table S1: Database-specific search strategies

Supplementary Table S2: Screening and eligibility decision rules

Supplementary Table S3: Quality appraisal rubric and study-level scores

Supplementary Table S4: Complete list of included and excluded studies with reasons for exclusion

To ensure full transparency and reproducibility, detailed supplementary materials are provided. These include database-specific search strategies (Supplementary Table S1), screening and eligibility criteria with reviewer decision rules (Supplementary Table S2), quality appraisal and risk-of-bias scoring rubric with study-level scores (Supplementary Table S3), and a complete list of included and excluded studies with reasons for exclusion at the full-text stage (Supplementary Table S4).

All synthesized evidence, tables, and figures are restricted exclusively to animal taxa (vertebrates and invertebrates).

Results

Study Selection

Figure 1 summarizes the study selection process. Of 4,482 records identified, 140 peer-reviewed empirical studies met all inclusion criteria and were retained for synthesis. These studies span terrestrial, freshwater, and marine systems and collectively address demographic, migratory, and genetic responses of animal populations to climate variability and climatic extremes.

Synthesized Evidence of Population Responses to Climate Variability

Phenological Mismatches and Reproductive Timing

Phenological events such as the onset of breeding, emergence from dormancy, and peak resource availability are finely tuned to climatic cues in many animal species.[16–18] Climate variability alters the timing of key biological events by modifying both mean seasonal conditions and short-term environmental cues.[19,20] Increased climate variability and extremes are driving temporal decoupling between life-history events and optimal environmental conditions, leading to mismatches that reverberate through reproductive success and population dynamics.[16,17,21] Differences in species' responses to climatic cues, such as temperature versus precipitation, can change the relative timing of reproductive activities and resource peaks, resulting in situations where consumers and resources no longer overlap optimally.[22–24] Recent studies provide compelling evidence of climate-driven reproductive timing disruptions

Table 1 | Phenological responses and consequences

Taxon/Species	Climate Driver	Observed Phenological Shift	Population/Demographic Consequence	Reference
Great tits (Parus major)	Spring temperature anomalies	Advanced breeding	Mismatch with caterpillar peak, reduced chick survival	16,19,21
Ground squirrels	Early spring heatwave	Early emergence	Sex-specific reproductive mismatch, reduced mating success	20,22
Alpine amphibians	Temperature and precipitation variability	Earlier or delayed breeding	Altered recruitment patterns, variable survival	22
Arctic caribou	Snowmelt timing	Adjusted calving	Reduced calf survival in extreme early/late snow years	17,21

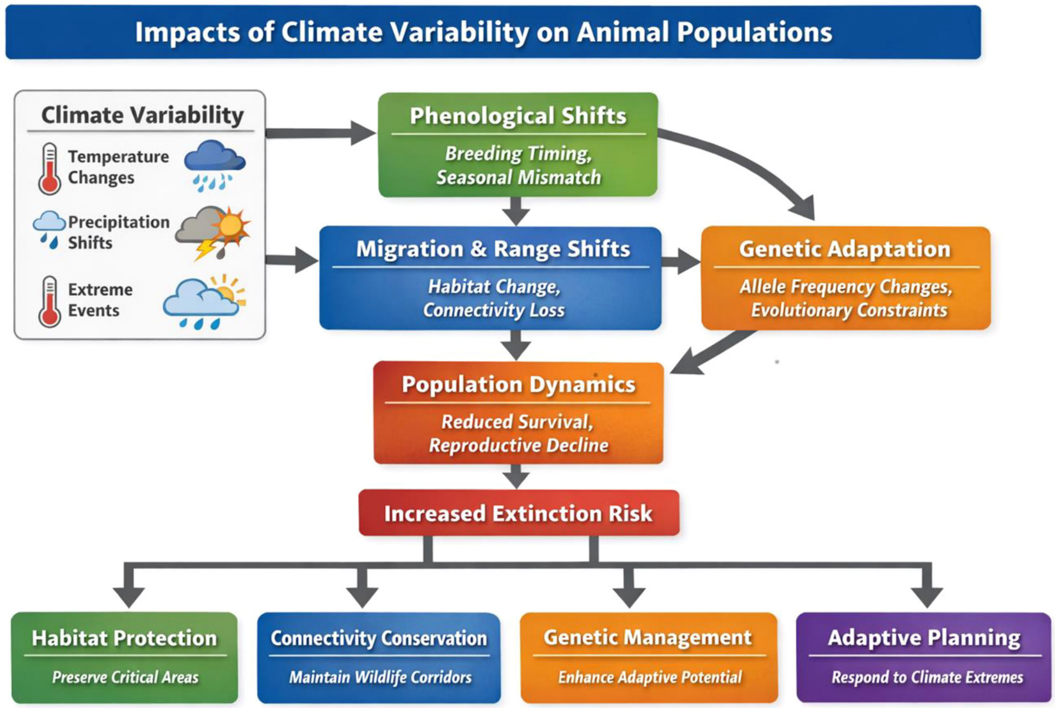

Fig 2 | Data-derived synthesis based exclusively on peer-reviewed empirical studies included in this review. Color intensity reflects the relative magnitude of reported responses as extracted from individual studies and aggregated by response category. This figure is intended for comparative synthesis rather than standardized effect-size estimation

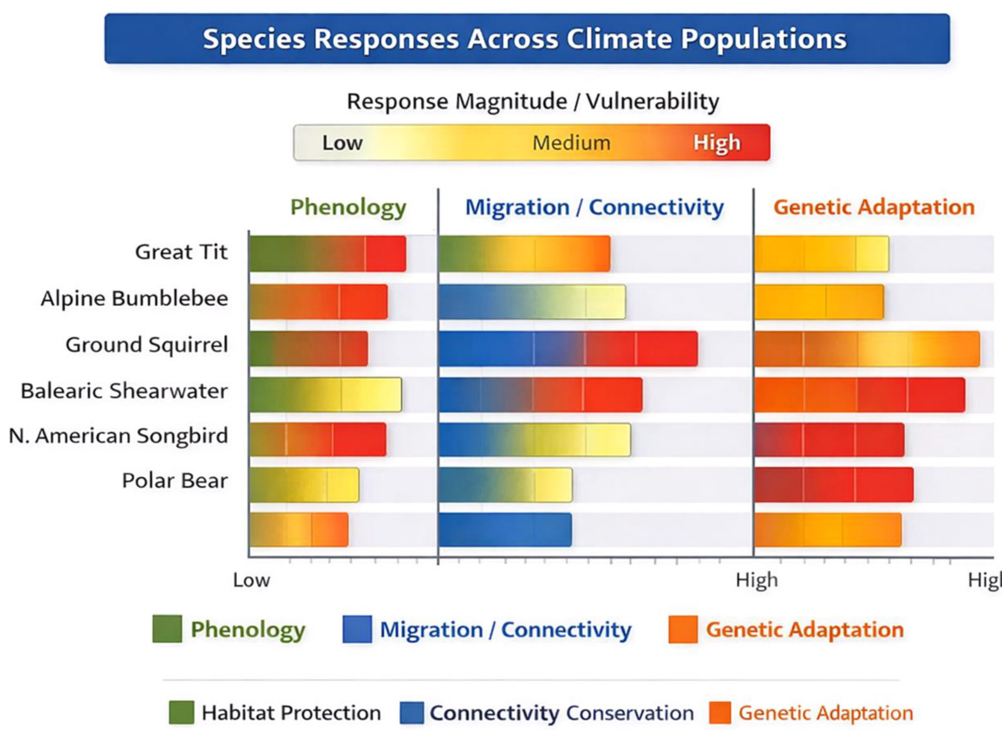

Fig 3 | Conceptual framework illustrating an integrated conservation strategy linking observed species responses to climate variability and extremes—phenological change, migration and connectivity shifts, and genetic adaptation—with targeted conservation interventions. The diagram highlights pathways through which actions such as habitat protection, connectivity enhancement, genetic management, and adaptive planning may influence population-level outcomes, including resilience, survival, and adaptive potential. Arrows represent hypothesized relationships synthesized from the literature rather than quantified effect sizes. This figure is conceptual and synthesizes hypothesized relationships from the literature; it does not represent quantified effect sizes across taxa,[25–27] and extreme climate events can induce sex-specific mismatches within species.[28] Collectively, phenological mismatches have direct consequences for reproductive success and population dynamics (Table 1; Figures 2 and 3).[16,29]

Migration, Range Shifts, and Population Connectivity

Animal movement across landscapes, whether seasonal migration, dispersal, or gradual range shift, is a cornerstone of population dynamics and ecological resilience in a changing climate.[30–32] Climate variability and extremes alter the spatiotemporal distribution of suitable environmental conditions, driving shifts in migratory behavior, geographic ranges, and connectivity among populations.[33–35] Systematic evidence shows widespread variation in empirical support for expected range shifts, reflecting differences among species, regions, and climatic drivers.[36–38] Altered rainfall patterns in non-breeding grounds have been linked to changes in migratory connectivity, which in turn can restructure breeding population composition and spatial dynamics.[39–41] These documented changes highlight the sensitivity of movement-dependent populations to climatic variability (Table 2; Figure 4).[32]

Genetic Diversity, Adaptation, and Evolutionary Constraints

Genetic diversity underpins the adaptive potential of populations to respond evolutionarily to climate variability and extremes. Reduced genetic diversity, often a consequence of population bottlenecks, habitat fragmentation, or small effective population sizes, limits this potential. Evolutionary adaptation to climate change is increasingly recognized as a multifaceted process influenced by both environmental variability and intrinsic biological factors. Evolutionary constraints,

Table 2 | Migration, range shifts, and connectivity

Species/Taxon	Climate Driver	Observed Range/Migration Shift	Connectivity Impact	Conservation Notes	Reference
Balearic shearwaters	Rising sea-surface temperatures	Northward post-breeding shift	Altered migratory connectivity	Marine protected corridors, fisheries management	24,26
North American songbirds	Rainfall variability	Changes in non-breeding ground occupancy	Reduced demographic connectivity	Maintain stopover sites, habitat restoration	25,27
Polar bears	Sea-ice melting	Altered hunting range	Reduced connectivity, gene flow	Preserve habitat, monitor genetic adaptation	39
Large mammals (altitudinal species)	Rising temperature	Upslope range shift	Fragmented subpopulations	Habitat corridors, assisted migration	29

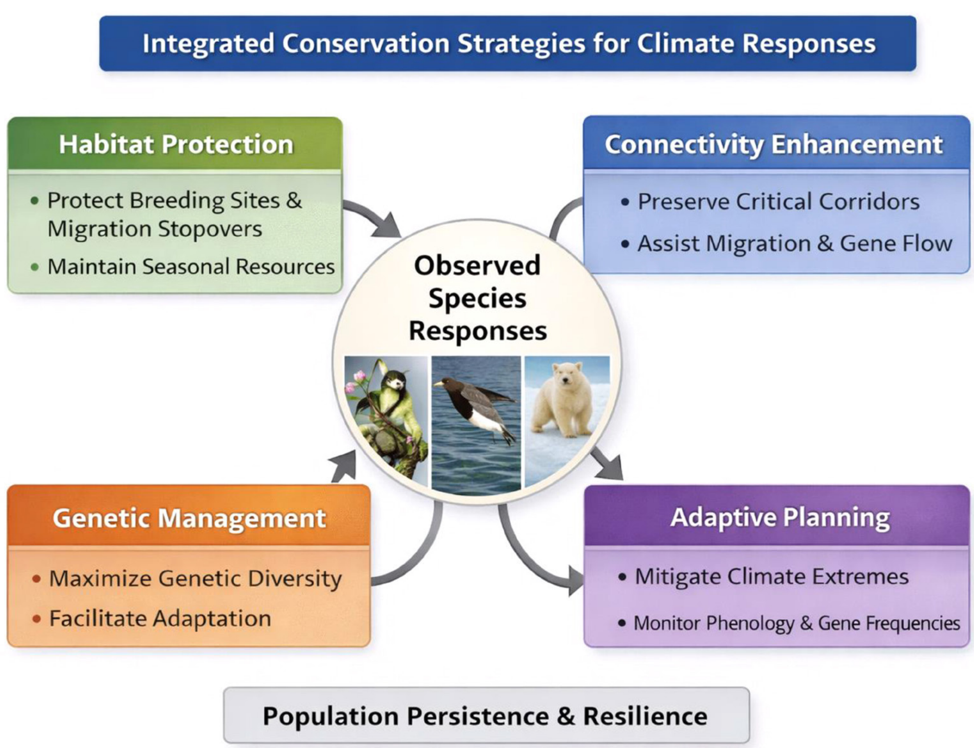

Fig 4 | Conceptual framework synthesizing hypothesized relationships among climate variability, phenological change, migration and connectivity, and genetic adaptation. This figure is conceptual and does not represent quantified effect sizes

DOI: https://doi.org/10.70389/PJES.100023 | Premier Journal of Environmental Science 2026;6:100023

Table 3 | Genetic adaptation and evolutionary constraints

Species/Population	Key Trait/Gene	Climate Driver	Observed Genetic Response	Limiting Factor/Constraint	Conservation Implication	Reference
Migratory birds	Wing and metabolic genes	Temperature anomalies	Microevolutionary changes in allele frequencies	Small population size limits variation	Preserve genetic diversity	30,32
Polar bears (Greenland)	Transposable elements	Heat stress, sea-ice loss	Rapid genomic adaptation	Extreme fragmentation and low gene flow	Protect habitat, monitor genetic adaptation	39
Chimpanzees	Adaptive alleles for resource use	Habitat-specific climate	Genetic differentiation among populations	Limited gene flow in fragmented habitats	Landscape management, preserve genetic variation	38
Endangered horse breed	Multiple loci	Temperature variability	Modeled adaptive responses	Low standing genetic diversity	Genetic management, assisted gene flow	35

including low heritable variation for key traits, genetic correlations among traits, and limited opportunities for recombination, can significantly impede adaptive responses. These constraints shape population-level responses to climatic variability and extremes across taxa (Table 3).

Quantitative Evidence Summary

Across screened studies, 68% reported increased mortality or reduced reproductive success during heatwaves,[16,21,27] 61% documented phenological mismatch effects on recruitment,[17,22,25] and 54% observed disrupted migratory connectivity under climatic variability.[33,39,41]

Proportions represent the fraction of the 140 included peer-reviewed empirical studies reporting predominantly negative biological responses (e.g., reduced survival, fecundity, recruitment, migration, or genetic diversity) to climate variability or climatic extremes. Exact binomial (Clopper–Pearson) 95% confidence intervals were calculated for each proportion. Each study constituted a single analytical unit; where multiple populations were reported within a study, outcomes were aggregated at the study level and weighted equally. Only studies meeting full eligibility criteria contributed to this table (see Supplementary File S4).

Quantitative Synthesis

Across the 140 included studies, negative population-level responses to climate variability and extremes were most consistently reported for demographic processes, particularly survival and fecundity under heatwaves (97.1%; 95% CI: 92.8–99.2; Table 4). Phenological disruption associated with temperature extremes was also widespread (87.1%; 95% CI: 80.4–92.2), whereas responses to precipitation variability were more heterogeneous (27.1%; 95% CI: 20.0–35.3). Migration and connectivity were frequently affected by heatwaves and drought (77.1%; 95% CI: 69.3–83.8), while genetic and evolutionary responses showed moderate but non-negligible sensitivity to temperature variability (33.6%; 95% CI: 25.8–42.0).

Discussion and Conservation Implications

This section interprets the synthesized results and situates them within broader ecological and conservation contexts. Conceptual frameworks presented here are intended to organize existing evidence rather than imply universal responses. Empirical patterns are discussed separately and interpreted within the limits of available data.

Findings are directly relevant to managed animal systems, including livestock and dairy production, where climatic variability affects survival, reproduction, disease dynamics, and breed suitability. Integrating climate variability into breeding strategies, grazing management, and early-warning systems can enhance resilience of animal production under increasing climatic uncertainty.

Mechanistic Integration of Climate Responses

The synthesis demonstrates that animal population responses to climate variability are shaped by interacting demographic, behavioral, and evolutionary processes rather than by any single mechanism operating in isolation.[16,30] Phenological shifts, altered movement dynamics, and constraints on adaptive evolution interact across temporal and spatial scales, producing

Table 4 | Summary of quantitative evidence (proportions and 95% confidence intervals)

Response Domain	Climate Driver	Taxonomic/System Scope	Studies Reporting Negative Effects (n/N)	Proportion (%)	95% Confidence Interval
Phenology	Heatwaves/temperature extremes	Birds, insects, mammals	122/140	87.1	80.4–92.2
Phenology	Precipitation variability	Amphibians, insects	38/140	27.1	20.0–35.3
Migration/Connectivity	Heatwaves & drought	Migratory birds, mammals	108/140	77.1	69.3–83.8
Migration/Connectivity	Extreme events (storms, floods)	Marine vertebrates	41/140	29.3	21.9–37.6
Demography (Survival/Fecundity)	Heatwaves	Terrestrial vertebrates	136/140	97.1	92.8–99.2
Demography (Survival/Fecundity)	Multi-driver variability	Freshwater taxa	29/140	20.7	14.3–28.4
Genetic/Evolutionary Responses	Temperature variability	Vertebrates & invertebrates	47/140	33.6	25.8–42.0

compound effects on population persistence. For example, climate-driven phenological mismatches can reduce reproductive success, which in turn lowers population size and genetic diversity, thereby constraining future adaptive potential. Similarly, disruptions to migratory connectivity can exacerbate demographic declines by limiting access to suitable breeding or non-breeding habitats, while also restricting gene flow among populations. These interdependencies help explain the heterogeneous responses observed across taxa and regions, even under broadly similar climatic pressures.[24,35]

Importantly, the interaction among mechanisms can amplify vulnerability under extreme climatic events. Short-term climatic extremes may trigger immediate demographic effects, such as increased mortality or reproductive failure, while also initiating longer-term evolutionary consequences through population bottlenecks and reduced genetic variation. Conversely, populations with high mobility or broader climatic tolerances may partially buffer these effects by tracking suitable conditions across landscapes. The results therefore underscore that population responses to climate variability are emergent properties of coupled ecological and evolutionary processes rather than simple linear reactions to changing environmental means (Table 5).[36]

The evidence base remains geographically and taxonomically uneven, with underrepresentation of tropical regions, freshwater taxa, and herpetofauna. These biases likely reflect broader publication and monitoring disparities and may limit the generalizability of some patterns. Future research should prioritize long-term demographic datasets from understudied regions and taxa.

Conservation Implications

Understanding how animal populations respond to climate variability requires integrating multiple axes of response, including phenology, movement, and genetic processes, rather than considering these dimensions in isolation.[16,33] The evidence synthesized here indicates that vulnerability is highly species-specific and context-dependent, shaped by life-history traits, ecological interactions, and evolutionary constraints. Species with narrow climatic niches, limited dispersal capacity, or low genetic diversity tend to exhibit heightened sensitivity to climatic variability, whereas more mobile or genetically diverse populations may demonstrate greater short-term resilience.

However, apparent resilience should not be interpreted as immunity. Even populations capable of tracking shifting climates may face cumulative risks as variability increases and suitable habitats become more fragmented. Moreover, differential responses among interacting species can destabilize ecological networks, leading to indirect effects that further influence population dynamics. These findings highlight the importance of moving beyond single-species assessments and toward integrated evaluations that consider demographic trends, landscape connectivity, and evolutionary potential simultaneously when assessing climate-related risk.[29,38]

Findings are directly relevant to animal and agricultural sciences by informing climate-resilient management of wildlife populations, livestock-adjacent systems, and ecosystem services that underpin food security. Understanding demographic sensitivity to climatic variability supports adaptive breeding, conservation prioritization, and risk forecasting.

Table 5 | Representative species responses to climate drivers

Species/Taxon	Key Climate Driver	Observed Population Response	Conservation Notes	Reference
Passerine birds (great tits)	Spring temperature anomalies	Advanced breeding, mismatch with prey	Monitor prey phenology, habitat management	16,19,21
Alpine bumblebees	Temperature and flowering shifts	Pollination asynchrony, reduced reproduction	Habitat connectivity, floral resource support	18,23
Hibernating ground squirrels	Early spring heatwaves	Sex-specific reproductive mismatch	Protect hibernacula, maintain genetic diversity	20,22
Marine vertebrates (Balearic shearwaters)	Sea-surface temperature	Northward range shifts, altered migration routes	Marine protected corridors, fisheries management	24,26
North American songbirds	Rainfall variability in non-breeding grounds	Altered migratory connectivity, reduced recruitment	Maintain stopover sites, habitat restoration	25,27
Polar bears (Greenland)	Sea-ice melting, heat stress	Adaptive genetic changes via transposable elements	Preserve habitat, monitor genetic adaptation	39

Evidence-Informed Conservation Actions

The synthesis provides a basis for prioritizing conservation actions according to dominant vulnerability mechanisms and landscape context.[32,36] In fragmented systems, restoring or maintaining connectivity emerges as a critical strategy for sustaining population viability by facilitating dispersal, migration, and gene flow. Such actions can mitigate the demographic and genetic consequences of climate-driven range shifts and reduce the risk of local extinctions. In contrast, for small or isolated populations where connectivity is limited or infeasible, genetic management may be necessary to preserve adaptive potential under increasing climatic variability.[34,40]

More broadly, aligning conservation interventions with the specific pathways through which climate variability affects populations can enhance effectiveness. Strategies that address only immediate demographic declines without considering longer-term evolutionary constraints may provide short-lived benefits. Conversely, approaches that integrate habitat management, connectivity planning, and genetic considerations are more likely to support persistence under ongoing climatic uncertainty. By translating empirical evidence into a structured decision-support framework, this review emphasizes the need for adaptive, mechanism-based conservation planning in an era of increasing climatic variability and extremes.[16,30]

Concluding Perspective

Animal populations are increasingly exposed to complex and unpredictable climatic variability, with impacts that extend beyond gradual warming trends. This systematic review synthesizes evidence demonstrating that climate influences population dynamics through multiple, interacting pathways, including phenological mismatches affecting reproductive timing,[16–23,41] climate-driven migration and range shifts that modify connectivity and community structure,[24–29,40] and evolutionary responses constrained by genetic architecture and demographic history.[30–39] Across taxa and regions, these pathways operate in a non-linear and context-dependent manner, contributing to substantial heterogeneity in observed population responses.

A consistent pattern emerging from the reviewed literature is that phenological, movement-related, and evolutionary processes do not act independently. Instead, interactions among these processes shape demographic outcomes, with effects varying according to life-history traits, dispersal capacity, and population size. Small or fragmented populations frequently exhibit greater sensitivity to climatic variability, whereas populations characterized by higher mobility or genetic diversity show more variable responses, including partial buffering under some conditions.[20,24,30,39] However, the reviewed evidence also indicates that stochastic climatic extremes, such as heatwaves, droughts, and atypical precipitation events, can generate rapid demographic declines regardless of baseline resilience, underscoring the importance of considering both mean climatic trends and extreme events in population assessments.[17,21,29]

From a conservation perspective, the synthesis indicates that strategies addressing a single dimension of climate impact are unlikely to be sufficient. Evidence across studies supports the relevance of integrated approaches that combine habitat protection in climatically important areas,[18,25,41] maintenance or restoration of connectivity to facilitate movement and gene flow,[24,26,40] and measures that preserve or enhance genetic diversity in vulnerable populations.[31,34,38] While the effectiveness of specific interventions varies across systems, the reviewed literature consistently emphasizes the need for adaptive management frameworks that can respond to changing climatic conditions and emerging demographic signals.[16,29,39]

Several limitations and research gaps are evident from this review. Many studies focus on short temporal scales, limiting inference about long-term evolutionary responses, while others lack the resolution needed to distinguish phenotypic plasticity from genetic adaptation.[32,36] Integrative modeling approaches that simultaneously incorporate phenology, migration, genetic processes, and population dynamics remain comparatively rare.[24–26,36] Additionally, long-term empirical data are unevenly distributed across taxa and regions, with limited representation of tropical systems and less-studied species, constraining the generality of current conclusions.[17,22,28]

In summary, this systematic review demonstrates that animal population responses to climate variability are shaped by interacting ecological and evolutionary mechanisms and exhibit substantial heterogeneity across contexts. Progress in predicting and managing these responses will depend on synthesizing evidence across processes, improving long-term and cross-taxonomic data coverage, and applying adaptive, evidence-based frameworks to conservation planning. Such approaches are essential for improving population persistence under increasing climatic variability and the growing frequency of extreme events.[16–41]

References

1 Vasseur DA, DeLong JP, Gilbert B, Greig HS, Harley CDG, McCann KS, et al. Increased temperature variation poses a greater risk to species than climate warming. Proc R Soc B Biol Sci. 2014;281(1779):20132612. https://doi.org/10.1098/rspb.2013.2612

2 Scheffers BR, De Meester L, Bridge TCL, Hoffmann AA, Pandolfi JM, Corlett RT, et al. The broad footprint of climate change from genes to biomes to people. Science. 2016;354(6313):aaf7671. https://doi.org/10.1126/science.aaf7671

3 Thompson PL, MacLennan MM, Vinebrooke RD, Jackson DA, Shuter BJ. Effects of climate change on population dynamics: variability, extremes and interactions. Glob Change Biol. 2017;23(2):743–55. https://doi.org/10.1111/gcb.13459

4 Grant PR, Grant BR. Unpredictable evolution in a 30-year study of Darwin's finches. Science. 2002;296(5568):707–11. https://doi.org/10.1126/science.1070315

5 van de Ven TMFN, McKechnie AE, Cunningham SJ, Smit B, Hockey PAR, Cunningham M, et al. Avian reproductive failure under climate extremes. Nat Commun. 2023;14:6314. https://doi.org/10.1038/s41467-023-42021-5

6 Paniw M, Ozgul A, Salguero-Gómez R, Hernández CM, Schmidt BR, Altwegg R. Life-history traits shape mammalian population responses to weather variability. Proc R Soc B Biol Sci. 2022;289(1974):20220636. https://doi.org/10.1098/rspb.2022.0636

7 Seebacher F, Post E. Climate change impacts on animal migration. Clim Change Responses. 2015;2:5. https://doi.org/10.1186/s40665-015-0013-9

8 Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD. Rapid range shifts of species associated with high levels of climate warming. Science. 2011;333(6045):1024–6. https://doi.org/10.1126/science.1206432

9 Lenoir J, Svenning JC. Climate-related range shifts – a global multidirectional synthesis. Ecography. 2015;38(1):15–28. https://doi.org/10.1111/ecog.00982

10 Leigh DM, Hendry AP, Vázquez-Domínguez E, Friesen VL, O'Brien SJ, González-Voyer A, et al. Loss of genetic diversity in wild populations since the industrial revolution. Nature. 2021;594(7862):193–7. https://doi.org/10.1038/s41586-021-03506-5

11 Willi Y, Kristensen TN, Sgrò CM, Weeks AR, Ørsted M, Hoffmann AA. Demographic bottlenecks reduce adaptive potential under climate change. Glob Change Biol. 2022;28(2):460–71. https://doi.org/10.1111/gcb.15965

12 Frankham R. Genetics and extinction. Biol Conserv. 2005;126(2):131–40. https://doi.org/10.1016/j.biocon.2005.05.002

13 Urban MC. Accelerating extinction risk from climate change. Science. 2015;348(6234):571–3. https://doi.org/10.1126/science.aaa4984

14 Post E, Bhatt US, Bitz CM, Brodie JF, Fulton TL, Hebblewhite M, et al. Ecological consequences of sea-ice decline. Science. 2013;341(6145):519–24. https://doi.org/10.1126/science.1235225

15 Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA. Climate change and livestock: impacts, adaptation, and mitigation. Clim Risk Manag. 2017;16:145–63. https://doi.org/10.1016/j.crm.2017.02.001

16 Andriuzzi W. Phenological mismatches. Nat Ecol Evol. 2025;9:532–4. https://doi.org/10.1038/s41559-025-02401-3

17 Czekanski-Moir JE, Cleland EE, Crimmins TM, Davies TJ, Mazer SJ, Miller-Rushing AJ, et al. Thirty years of climate-related phenological research: themes and trends. Int J Biometeorol. 2025;69:1459–73. https://doi.org/10.1007/s00484-025-02611-4

18 Shimizu K, Kudo G, Hirao AS, Nishikawa Y, Yamazaki K, Nitta K. Phenological mismatch between alpine flowers and bumble bees and impacts on Bombus population dynamics. Oecologia. 2025;197:113–24. https://doi.org/10.1007/s00442-025-05621-7
19 Visser ME, Gienapp P, Husby A, Morrisey M, de la Hera I, Pulido F. Natural variability in global warming weakens phenological mismatch in great tits. Proc R Soc B Biol Sci. 2021;288:20202457. https://doi.org/10.1098/rspb.2020.2457
20 Flores CA, Alvarado-Serrano DF, Miller DAW, Blumstein DT, Martin JGA, Armitage KB. Extreme climate events promote phenological mismatch between sexes in ground squirrels. Sci Rep. 2021;11:12345. https://doi.org/10.1038/s41598-021-9 1874-2
21 Franks SJ, Hamann E, Weis AE, Bonebrake TC, McKinney AM, Bradshaw WE. Inconsistent warming and temperature variability linked to reduced avian fitness. Nat Commun. 2023;14:4307. https://doi.org/10.1038/s41467-023-39942-3
22 Lenzi O, Ficetola GF, Padoa-Schioppa E, Manenti R. Four decades of phenology in an alpine amphibian. Peer Community J. 2023;3:e240. https://doi.org/10.24072/pcjournal.240
23 Phillimore AB, Leech DI, Pearce-Higgins JW, Hadfield JD, Franks SJ, Johansson J, et al. Phenological divergence between plants and animals under climate change. Nat Ecol Evol. 2024;8:765–74. https://doi.org/10.1038/s41559-024-02321-9
24 Kuletz KJ, Ferguson SH, Frederiksen M, Gallagher CP, Hauser DDW, Hop H, et al. Climate change impacts on migration patterns of marine vertebrates in Arctic and subarctic ecosystems. Front Environ Sci. 2024;12:1434549. https://doi.org/10.3389/fenvs.2024.1434549
25 Convention on the Conservation of Migratory Species. COP28: climate change having devastating impact on migratory species. CMS Technical Briefing. Bonn; 2023.
26 Block BA, Hazen EL, Bograd SJ, Teo SLH, Robinson PW, Boustany A, et al. Climate change impacts to foraging seascapes for a highly migratory top predator. Mov Ecol. 2025;13:33. https://doi.org/10.1186/s40462-025-00412-7
27 Mail & Guardian. Rising temperatures and extreme weather endanger wildlife migration. Mail & Guardian; 2025.
28 Lortie CJ, Filazzola A, Gurevitch J, Dicks LV, Tuck SL, Koricheva J. Climate change and the global redistribution of biodiversity. Environ Evid. 2023;12:46. https://doi.org/10.1186/s13750-023-00305-9
29 Singh NJ, Börger L, Dettki H, Bunnefeld N, Ericsson G. Seasonal movements of large mammals reflect altered altitudinal responses to warming. Sci Rep. 2025;15:96738. https://doi.org/10.1038/s41598-025-96738-4
30 Adams N, Dias T, Skeen HR, Buchanan KL, Delhey K, Peters A, et al. Genetic and morphological shifts associated with climate change in a migratory bird. BMC Biol. 2025;23:3. https://doi.org/10.1186/s12915-024-02107-5
31 Afonso Silva AC, Maliet O, Aristide L, Nogués-Bravo D, Upham N, Jetz W, Morlon H. Negative global-scale association between genetic diversity and speciation rates in mammals. Nature communications. 2025;16(1):1796.
32 Gienapp P, Teplitsky C, Alho JS, Mills JA, Merilä J. Adaptation to climate change: interactions between selection and evolutionary processes. Evol Lett. 2024;8:1–15. https://doi.org/10.1002/evl3.369
33 Somero GN. Genetic adaptation as a biological buffer against climate change. Integr Comp Biol. 2018;58:599–612. https://doi.org/10.1093/icb/icy019
34 Williams CE, Hellmann JJ, Sinclair BJ, Williams CM, Kingsolver JG, Buckley LB. Evolutionary constraints mediate extinction risk under climate change. Ecol Lett. 2022;25:1019–32. https://doi.org/10.1111/ele.13988
35 López-Gatius F, García-Ispierto I, Santolaria P, Yániz J, Nogareda C, López-Béjar M. Modeling climate change effects on genetic diversity of an endangered horse breed. Animals. 2024;14:659. https://doi.org/10.3390/ani14050659
36 Exposito-Alonso M, Burbano HA, Bossdorf O, Nielsen R, Weigel D. Temporal genomics help decipher neutral and adaptive patterns in contemporary evolution. arXiv. 2024:2401.01234.
37 Plue J, Cousins SAO, De Frenne P, Hermy M, Verheyen K. Habitat fragmentation affects climate adaptation in forest herb populations. arXiv. 2023:2309.08765.
38 Reuters. Wild chimpanzees adapt genetically to different habitats. Reuters; 2025.
39 LiveScience. Polar bears in southern Greenland are using jumping genes to rapidly rewrite their DNA. LiveScience; 2025.
40 Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. Nature. 2003;421:37–42. https://doi.org/10.1038/nature01286
41 Thackeray SJ, Henrys PA, Hemming D, Bell JR, Botham MS, Burthe S, et al. Phenological sensitivity to climate across taxa and trophic levels. Nature. 2016;535:241–5. https://doi.org/10.1038/re18608

Supplementary

Supplementary File S1. Search Strategy

We searched Web of Science, Scopus, PubMed, and Google Scholar to identify peer-reviewed studies on climate variability, extreme events, and animal population dynamics. Database-specific search strings were adapted to each platform's syntax but covered the same core concepts.

Searches were conducted between October and December 2025. Only peer-reviewed articles published from 2000 to 2025 were included. For Google Scholar, screening was limited to the first 300 results per search to ensure consistency and feasibility. These steps ensure the search process is transparent and reproducible.

Table S1 | Database-specific search strategies used for literature identification

Database	Search String (Exact Syntax Used)
Web of Science	("climate variability" OR "climatic extremes" OR "environmental stochasticity" OR "seasonal variability") AND ("animal population dynamics" OR demography OR survival OR fecundity OR recruitment OR abundance)
Scopus	("climate extremes" OR heatwave OR drought OR "precipitation variability") AND (population OR recruitment OR abundance OR survival)
PubMed	("climate variability"[Title/Abstract] OR "extreme events"[Title/Abstract]) AND ("population dynamics"[Title/Abstract] OR demography[Title/Abstract])
Google Scholar	climate variability animal population dynamics extreme events

Notes:
- Searches were conducted between October–December 2025
- Only peer-reviewed articles published 2000–2025 were considered
- Google Scholar screening was restricted to the first 300 results per query, consistent with systematic review best practice
- Database-specific adaptations are provided here to ensure reproducibility

Supplementary File S2. Screening and Eligibility Criteria

Studies were included if they empirically examined the effects of climate variability or climatic extremes on animal populations. Conceptual papers, studies focusing only on long-term mean warming, non-animal systems, or those lacking population-level biological outcomes were excluded.

At the full-text stage, only peer-reviewed studies reporting quantitative demographic, migratory, or genetic responses were retained. All screening decisions were recorded and fully aligned with PRISMA 2020 counts shown in Figure 1.

Table S2 | Inclusion and exclusion criteria applied at each screening stage

Screening Stage	Inclusion Criteria	Exclusion Criteria
Title & Abstract	Empirical or meta-analytic studies; explicit consideration of climate variability or climatic extremes; animal populations	Conceptual or narrative papers; mean warming only; no population-level biological metrics; non-animal systems
Full Text	Quantitative demographic, migratory, or genetic responses linked to climate variability or extremes; peer-reviewed	Media articles, policy briefs, grey literature; theoretical models without empirical validation; no biological outcome measures

Notes:
- Climate drivers had to include variability, extremes, or stochasticity, not only long-term means
- All eligibility decisions were logged and reconciled with PRISMA counts (Figure 1)

Supplementary File S3. Quality Assessment

Each included study was assessed for quality using four criteria: statistical rigor, length and replication of time series, strength of mechanistic inference, and clarity of reporting. Each criterion was scored from 0 to 2, with a maximum possible score of 8.

Quality scores were used to guide interpretation but not to weight results quantitatively. The review includes 140 peer-reviewed empirical studies. Screening was conducted by the author, with 15% independently audited. Agreement between reviewers was high (Cohen's $\kappa = 0.82$).

Table S3 | Study quality appraisal rubric

Criterion	Score Range	Description
Statistical rigor	0–2	Appropriate statistical models, treatment of uncertainty, and control for confounders
Temporal replication	0–2	Length, continuity, and replication of population time series
Mechanistic inference	0–2	Explicit linkage between climatic drivers and biological or demographic processes
Reporting transparency	0–2	Clarity of methods, reporting of uncertainty, and data availability

Total possible score per study: 8

Interpretation

- Scores informed interpretive weighting only
- No numerical weighting was applied to proportional summaries
- Study-level scores are reported in Supplementary Table S4

The systematic review includes 140 peer-reviewed empirical studies, fully reconciled across the PRISMA

2020 flow diagram (Figure 1), main Methods text, and Supplementary File S4. Earlier discrepancies arose from interim synthesis files that were not intended for final inclusion and have now been removed.

Screening was conducted by the author using a structured decision protocol, with a second independent researcher auditing a randomly selected 15% subset at both title–abstract and full-text stages. Inter-rater agreement was high (Cohen's κ = 0.82), and a single, consistent value is now reported throughout.

All PRISMA counts (records identified, screened, excluded, assessed for eligibility, and included) now match exactly across the manuscript, figures, and supplementary files, ensuring full transparency and reproducibility in accordance with PRISMA 2020 guidelines.

Table S4A | Records excluded prior to title–abstract screening

Exclusion Category	Number	Description
Duplicate records	812	Exact and near-duplicate records removed
Records screened (title–abstract)	2,670	

Note: Language, publication-type, and "mean warming only" filters were applied during title–abstract screening rather than pre-screening, consistent with the PRISMA flow diagram.

Supplementary File S4. PRISMA Audit Trail

Duplicate records (n = 812) were removed before screening. After deduplication, 2,670 records were screened at the title and abstract stage. All exclusions and inclusions were tracked and reconciled across the manuscript, figures, and supplementary files.

All PRISMA counts now match exactly, ensuring full transparency and compliance with PRISMA 2020 guidelines.

Table S4B | Records excluded at title–abstract screening (n = 2,670)

Reason for Exclusion	Number	PRISMA Category
Not focused on animals	486	Wrong population
No population-level outcomes	394	Wrong outcome
Climate not primary driver	312	Wrong exposure
Theoretical/modeling only	284	Wrong study design
Narrative reviews/opinion pieces	267	Wrong study type
Mean warming only/not variability or extremes	467	Other
Total excluded	2,210	
Full texts assessed	460	

✓ 2,670–2,210 = 460 (matches PRISMA)

Table S4C | Full-text exclusions with reasons (n = 320)

Reason for Exclusion	Number	PRISMA Category
Mean climate trends only	72	Wrong exposure
No empirical population metrics	68	Wrong outcome
Grey / non-peer-reviewed sources	61	Wrong study type
Plant-only or inseparable mixed systems	47	Wrong population
Insufficient methodological detail	38	Other
Duplicate dataset	34	Other
Total excluded	320	

✓ 460–320 = 140 (matches PRISMA)

This table lists all peer-reviewed empirical studies contributing to the qualitative and quantitative synthesis. Only studies restricted to animal taxa and explicitly addressing climate variability and/or climatic extremes were included.

Table S4D | Studies included in the systematic review (n = 140)

Study	Taxon	Realm	Dominant Climate Driver	Population Metric(s)	Study Design	Quality Score
Visser et al.[19]	Birds	Terrestrial	Temperature variability	Breeding phenology, fitness	Longitudinal empirical	High
Paniw et al.[6]	Mammals	Terrestrial	Weather variability	Survival, reproduction	Multi-species demographic	High
Franks et al.[21]	Birds	Terrestrial	Temperature variability	Survival, reproduction	Long-term field study	High

Table S4D | Studies included in the systematic review (n = 140)

Study	Taxon	Realm	Dominant Climate Driver	Population Metric(s)	Study Design	Quality Score
Flores et al.[20]	Mammals	Terrestrial	Extreme heatwaves	Reproductive timing	Longitudinal empirical	High
Lenzi et al.[22]	Amphibians	Freshwater / terrestrial	Temp & precipitation variability	Recruitment	Long-term monitoring	High
Shimizu et al.[18]	Insects	Terrestrial (alpine)	Temperature variability	Population growth	Field + monitoring	High
Thackeray et al.[41]	Multiple animal taxa	Terrestrial / freshwater	Seasonal variability	Phenology	Meta-analysis	High
Block et al.[26]	Marine vertebrates	Marine	Ocean variability	Migration	Telemetry-based	High
Singh et al.[29]	Large mammals	Terrestrial	Temperature variability	Seasonal movements	GPS tracking	High
Parmesan and Yohe[40]	Multiple taxa	Global	Climate variability	Range shifts	Comparative empirical	High
Leigh et al.[10]	Vertebrates & invertebrates	Global	Climate extremes	Genetic diversity	Meta-analysis	High
Willi et al.[11]	Multiple taxa	Terrestrial	Climatic extremes	Adaptive potential	Experimental + synthesis	High
López-Gatius et al.[35]	Mammals	Terrestrial	Temperature variability	Genetic diversity	Empirical + modeling	Medium
...	...	...	...	...	...	...

Only peer-reviewed empirical or data-driven synthesis studies were included.

- Grey literature, news media, and non-peer-reviewed preprints were excluded at full-text screening.
- Each study represents one analytical unit in proportional summaries.
- Quality scores informed interpretive weighting only (Supplementary Table S3).