FutureArcticLives

Mechanisms of Vulnerability and Resilience to Climate Change in Arctic Wildlife Populations

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Abstract

The Arctic is experiencing rapid transformation due to climate change, with temperatures rising nearly four times faster than the global average and species turnover projected to be five times greater than global levels. These high rates of change, are driven by Arctic amplification, that has have profound physical and ecological consequences, including sea ice loss, shifting seasonality, altered precipitation patterns, and expanding boreal vegetation. Here, we examine the impacts of climate change on Arctic biodiversity by reviewing 23 years of research on 66 Arctic vertebrate species, including fish, birds, and mammals, that are vital to local communities and ecosystems. Our study focuses on the mechanisms driving species responses to climate-induced changes, such as shifts in distribution, reproduction, and behavior, while identifying key factors contributing to population declines or resilience. We also evaluate the influence of climate pressures, such as sea ice loss, warming temperatures, and changing precipitation patterns, and explore the role of adaptive traits in species' ability to cope with these changes. We summaries the conducted literature research. Current studies are heavily focused on population trends and range shifts, primarily in birds, marine mammals, and economically significant fish species. However, research on life-history traits, phenological changes, physiological responses, and future-oriented scenarios are underrepresented in our literature review. Research on underrepresented species and ecosystems, while integrating long-term ecological data with climate models, will enhance understanding of Arctic biodiversity and inform adaptive management strategies.

1. Introduction

"The Arctic is losing its character and soul, its snow and ice" (1), while its future shape remains uncertain. With temperatures rising nearly four times faster than the global average and up to seven times faster in parts of Eurasia (2) and a projected species turnover five times greater than the global average (3), the Arctic represents one of the most rapidly transforming ecosystems on Earth. Physical and ecological consequences, including rising land and sea temperatures (4,5), changing ice cover and meltwater inputs (6), increased precipitation and extreme weather events (7–9), shifting seasonality (10), increased primary production (4), and expanding terrestrial vegetation (11), are reshaping the region and imposing unprecedented pressures on wildlife and local communities. While ecological changes in the Arctic are outpacing the ability of many species to adapt, they are also outstripping our scientific knowledge of Arctic systems, hampering management, mitigation and adaptation efforts (12,13). Trend assessments of Arctic biodiversity often reveal puzzling variability alongside large-scale processes, with some species or populations exhibiting less resilience, higher vulnerability, and some thriving in response to climate-driven shifts (13–18).

One of the most rapid and consequential large-scale processes is borealisation. Borealisation is the gradual transformation of Arctic ecosystems into subarctic (boreal) systems, replacing cold-adapted species with warm-adapted ones (15,19–21). Borealisation-driven shifts occur across all taxa, including zooplankton (22), fish (20,21,23,24), birds (25), and mammals (26), typically favouring high-fecundity generalists, such as fast-moving predators, including killer whales (*Orcinus orca*), Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) (20,27). Climate change also temporarily benefits globally endangered species, such as fin whales (*Balaenoptera physalus*), blue whales (*B. musculus*), humpback whales (*Megaptera novaeangliae*), and sei whales (*B. borealis*), which thrive due to receding sea ice and longer ice-free seasons that create new habitats and food sources (28,29). Other species, such as Arctic-nesting pink-footed geese (*Anser brachyrhynchus*) and Greenland barnacle goose (*Branta leucopsis*), benefit from warmer temperatures, with more extended vegetation growth periods boosting reproductive success and expanding their disjunct breeding populations (30–32). However, these shifts also heighten the climate vulnerability of Arctic species like Greenland halibut (*Reinhardtius hippoglossoides*), walrus (*Odobenus rosmarus*), Arctic Brünnich's Guillemot (*Uria lomvia*) and narwhals (*Monodon monoceros*), which are already highly sensitive to climate change due to their reliance on sea ice, specialized feeding habits, or narrow temperature niches (26,33–35). In Southeast Greenland, the loss of summer pack ice and warming oceans have led to an influx of boreal cetaceans, including long-finned pilot whales (*Globicephala melas*), humpback and fin whales, white-beaked dolphins (*Lagenorhynchus albirostris*), and killer whales, which now consume around 700,000 tons of fish and 1.5 million tons of krill annually (26). The increased competition for food affects native Arctic species, including narwhals and walruses, which are in decline, indicating a potential regime shift within the ecosystem (26). Killer whales, as new apex predators, consume an estimated >1,000 narwhals annually during their seasonal presence in the eastern Canadian Arctic, exemplifying the profound ecosystem-level modifications driven by climate change-related shifts in predator distributions (36). Rapid range expansions, such as Atlantic cod discovered over 1,000 km further north in East Greenland, surpass the predictive capabilities of current models (37) and disrupt predator-prey relationships, increasing species vulnerabilities (16,21,38). A striking example of climate-induced collapse occurred in the southeast Bering Sea, where unprecedented warming and sea ice loss from 2018 to 2019 triggered a borealization event, resulting in a population decline of over 90%, or approximately 47 billion snow crabs (*Chionoecetes opilio*) (15).

However, relationships are less straightforward than once thought, including for typically climate-vulnerable Arctic species (13,18). For example, while declining ice typically is linked to reduced polar bear density due to their reliance on sea ice for hunting and migration, changing local sea ice conditions in the Kane Basin, with thinner seasonal ice boosting biological production, have had positive effects on bear body condition and reproductive success (39–41). Additionally, a healthy polar bear sub-population in Southeast Greenland, discovered in 2022, has adapted to an extended ice-free period by using freshwater glacial mélange as a year-round hunting platform (42). Novel behaviours such as feeding on ice-trapped white-beaked dolphins (*Lagenorhynchus albirostris*)[43], scavenging eggs, chicks and adult birds in seabird colonies, and hunting adult reindeer (*Rangifer tarandus*) highlight the species' temporary adaptability (44–48). Evidence of climate adaptations in other species is also growing. Arctic-breeding migratory birds, such as Geese, are shifting their arrival and breeding timing (49) or rapidly expanding ranges or migration routes to mitigate the impacts of climate change (30,50). However, adaption capacities vary by region, as seen in high-Arctic geese, which adjust egg-laying less to earlier snowmelt than low-Arctic geese, affecting their breeding success (51).

Local human communities are also vulnerable to changing environmental conditions, as seen in the abrupt collapse of the Bering Sea snow crab fishery in 2022, valued at US$227 million (15). However, shifts in species ranges can also create new opportunities**,** such as increased catches of boreal cetaceans and bluefin tuna (*Thunnus thynnus*) and the expansion of processing industries in newly accessible ranges of Atlantic cod (*Gadus mouha*) (26,52,53).

Assessing and predicting the impacts of climate change on biodiversity has become a critical priority for researchers, managers, and policymakers. However, the complexity of species' responses to climate change presents a significant scientific challenge. Climate change pressures on species arise from abiotic factors (e.g., temperature increases, sea level rise, ocean acidification**),** biotic factors (e.g., habitat loss, competition from invasive species), and human responses (e.g., land use changes, biofuel expansion, exploitation), with impacts driven by the complex interplay of these force (54,55). A species' vulnerability to climate change, its susceptibility and inability to cope with adverse effects, depends on three key components: exposure (the magnitude of climatic variation in its habitat), sensitivity (intrinsic traits affecting tolerance), and adaptive capacity (the ability to adjust) (54–56). Mechanisms are the causal pathways or processes through which climate pressures influence species, determining their vulnerability to climate change (54). Key mechanisms include physiological alignment with changing conditions, habitat quality or availability shifts, altered interspecies interactions, disrupted phenology, and exacerbated threats like overharvesting or invasive species (54). However, impacts are not evenly distributed, with positive effects often observed at the 'leading edge' and adverse effects at the 'trailing edge,' determined by the geographical gradient and direction of climatic changes (54). Analyses that neglect the heterogeneity in responses and average data across diverse ecoregions can obscure regional variations and mask population trends (18). Correlative models, which assume static properties and overlook adaptation capacity, can oversimplify dynamics, leading to potential over- or underestimation (13,54,57,58). Trait-based assessments, linking biological traits to climate impacts, lack spatial precision, while mechanistic models offer detailed insights through process-based simulations but are limited to well-studied species (54,58). These limitations are particularly pronounced for poorly known species, those with small or shrinking ranges, and species that decline in some regions while expanding in others (54,58,59). In summary, assessing and predicting climate change impacts on biodiversity is challenging due to model limitations, ecological complexity, and rapid change. These factors contribute to high uncertainty and conflicting information on population status and responses, and they hinder our understanding of how climatic forces affect species and populations.

Here, we review observed and predicted trends in Arctic vertebrate populations, focusing on the key mechanisms driving their responses to climate-induced changes. Specifically, we examine the factors contributing to population declines, species thriving, and adaptation. Moreover, we identify the underlying mechanisms, the causal processes or sequences of interactions, through which climate change pressures (e.g., rising temperatures, altered precipitation patterns) lead to species-level effects such as shifts in distribution, changes in reproduction, or altered behaviour (54).

To achieve this, we reviewed 23 years of research on 66 Arctic vertebrate species, including fish, birds, and mammals, important to local households and the national economies in the European and Canadian Arctic. Understanding these mechanisms is particularly valuable, providing insights into the direct and indirect links between climate drivers and species responses. This understanding facilitates more accurate projections of future impacts and informs effective conservation strategies.

The findings highlight priority areas for conservation, offer critical insights into shifts in Arctic biodiversity, and support the development of adaptive management strategies to protect species and ensure sustainable use by local communities.

2. Method

2.1. Literature Search

We identified 66 species harvested by communities in Greenland using catch statistics from Statistics Greenland. A comprehensive literature search was conducted using Google Scholar™, with search terms including "species common and scientific name + Greenland," "climate change," "global warming," "threats," "hunting," and "global change." Additionally, institutional websites were reviewed, including those of the Greenland Institute of Natural Resources, the North Atlantic Fisheries Organization (NAFO), the International Council for the Exploration of the Seas (ICES), the International Whaling Commission (IWC), the North Atlantic Marine Mammal Commission (NAMMCO), and the Canada/Greenland Joint Commission for the Conservation of Narwhal and Beluga (JCNB). Reports, meta-analyses, and literature reviews were also scanned to ensure comprehensive data collection. Unlike systematic literature reviews, we did not exclude studies based on quality. This approach allowed us to consider less detailed studies, such as anecdotal evidence of adaptation or species sightings. However, we applied quality assessment criteria to evaluate the studies. Arctic ecosystem experts, identified through their publication records, were consulted to confirm the completeness and accuracy of the bibliography.

2.1.1. Categorization of Evidence and Climate Variables:
The original publications conducted analyses on various identifiable species units. While we retain these original units in our analyses, we refer to all such units as "populations" rather than distinguishing among populations, subpopulations, stocks, or regions for clarity and simplicity. These distinctions are maintained in our detailed analysis and are only mentioned when essential for understanding.

2.1.2. Impacts of climate change
We systematically recorded the impact's type and magnitude for each piece of evidence regarding climate change impacts on species. We documented effects across multiple levels, individual, population, and species, and noted changes in key metrics such as population trends, reproductive output, body condition, range and habitat use, and predation pressure. For each change observed, we assigned descriptive terms (e.g., increase, decline, stability) to indicate the direction of the effect of climate pressures. To maintain consistency, we adopted the typology proposed by Foden et al. 2019 (54). See Table 1, column impacts, for classifying these types of impacts on the population, subpopulation and individual level. This framework allowed us to map each observed effect to a standard set of categories. In addition, we recorded that value whenever the original evidence provided information on the relative or absolute magnitude of an impact. In summary, these terms were used to succinctly capture the nature (direction) and, when available, the strength (magnitude) of species' response to climate pressures.

2.1.3. Climate pressure
To compile a comprehensive list of pressures affecting species and populations, we categorized climate change impacts according to the associated climate variables and the direction of their associations with biological responses, e.g., Predictor: Sea ice extent; Response: Reproduction; Association: Negative. In this framework, “predictors” are the climate variables that drive change (e.g., sea ice extent, salinity, vegetation shifts), while “responses” represent the aspects of individuals, populations, or species that are affected (e.g., reproduction, body condition) (54). We excluded neutral effects because the absence of a detected effect does not constitute evidence that no effect exists. We differentiated pressures by three main types:

1. Abiotic Pressures**:** Species are exposed to atmospheric changes (e.g., rising temperatures, altered drought frequency), changes in the physical environment (e.g., sea level rise, increased storms), and direct effects of greenhouse gases (e.g., ocean acidification).
2. Biotic Pressures**:** Climate-driven shifts in ecological processes, such as changes in food availability, predation pressure, or competition from invasive species, pose additional risks to species and populations.
3. Human Response Pressures**:** Species are impacted by human activities aimed at mitigating climate change (e.g., renewable energy projects), adapting to its effects (e.g., land use changes, infrastructure development), or exacerbating historical pressures (e.g., hunting, habitat destruction).

This structured approach allows us to identify the diverse and interacting pressures species face and assess their role in driving population trends and adaptation mechanisms.

2.1.4. Identification of mechanisms:
To identify the mechanisms through which climate pressures affect species, we systematically catalogued the various ways climate change influences individual species. The mechanisms can be categorized into five categories (54):

1. Changes in physiological preferences or limits are represented by physiological misalignment with environmental conditions, which refers to species struggling to maintain homeostasis as their environments shift beyond their physiological tolerances.
2. Changes in habitat or microhabitat quality and resource availability are exemplified by habitat or microhabitat changes, where climate change alters the availability or suitability of key habitats.
3. Alterations in interspecific interactions are reflected by shifts in species relationships, such as predation or competition shifts due to environmental changes.
4. Shifts in phenology, including seasonal or daily timing, are captured by phenological disruptions, which occur when species experience mismatches in life cycle events, such as breeding or migration, due to changing climatic conditions.
5. Finally, the exacerbation of other threats, such as overharvesting, invasive species, or habitat destruction, is illustrated by synergy with non-climate threats, where climate change compounds existing pressures on Arctic species, making survival and adaptation even more challenging.

Additionally, each impact was categorized into “detrimental impacts” (e.g., declines in body condition) versus “beneficial impacts” (e.g., increases in body condition). These effects are visualized using a logical flow format to clarify and facilitate understanding, illustrating the pathways and interactions between climate pressures and species responses. Table 1 shows the impact category cross-tables with potential mechanisms and one example from the Arctic.

Table 1. Categories of impacts of climate change on different levels (population, subpopulation, individual), five mechanisms as potential response on impacts (physiological misalignment with environmental conditions, habitat/microhabitat changes, altered interspecific interactions, phenological disruptions, synergy with non-climate threats), and one example from the Arctic

Impact Category	Impact Metric	Potential Mechanisms	Arctic Example
Level: Species			
Population characteristics	1.1 Changes in population size	Habitat/microhabitat changes; synergy with non-climate threats	Declines in polar bear numbers where sea-ice loss is compounded by historical overharvesting (60)

Impact Category	Impact Metric	Potential Mechanisms	Arctic Example
Population characteristics	1.2 Changes in the proportion of mature individuals	Physiological misalignment with environmental conditions; habitat/microhabitat changes	In caribou, altered nutritional conditions may delay maturation due to lower juvenile growth rates and adult mass gain, critical for timely maturation and reproductive success (61)
Population characteristics	1.3 Changes in sex ratio	Physiological misalignment with environmental conditions	In Svalbard reindeer, increased winter precipitation reduced survival in males and increased female bias (62)
Population characteristics	1.4 Changes in magnitude/frequency of population fluctuations	Habitat/microhabitat changes	Modified lemming cycles under warming conditions, altering the amplitude of population fluctuations (63)
Population characteristics	1.5 Number of subpopulations	Habitat/microhabitat Changes	Increased fragmentation of polar bear subpopulations as continuous sea ice breaks into isolated patches (63)
Range characteristics	2.1 Changes in range size	Habitat/microhabitat changes	Polar bear ranges contract in areas where sea ice is absent during critical hunting seasons (64)
Range characteristics	2.2 Changes in range location	Altered interspecific interactions	Northward expansion of red foxes into tundra areas formerly occupied by Arctic foxes, driven by competitive interactions (65)
Range characteristics	2.3 Level of fragmentation	Habitat/microhabitat changes	Sea-ice fragmentation leading to isolated groups of polar bears, reducing connectivity, e.g., Kane Basin sub-population (66)
Genetic characteristics	3.1 Changes in genetic diversity	Habitat/microhabitat changes; synergy with non-climate threats	Reduced genetic diversity in bowhead whales, driven by historical overharvesting and ongoing habitat fragmentation (67)
Genetic characteristics	3.2 Changes in allele frequencies	Physiological misalignment with environmental conditions	Adaptive shifts in allele frequencies in fish in response to warming waters and heat stress (observed in the Mediterranean (68))
Level: Sub-population			
Subpopulation characteristics	4.1 Changes in subpopulation sizes	Habitat/Microhabitat Changes	Declines in coastal Polar bear subpopulation sizes in regions with severe sea-ice loss [69]
Subpopulation Characteristics	4.2 Changes in the probability of local extinction/colonization	Habitat/microhabitat changes	Human-induced borealisation and collapse of the Bering Sea snow crab (15)
Subpopulation characteristics	4.3 Changes in subpopulation sex ratio	Physiological misalignment with environmental conditions	Lower survival rates of pregnant polar bears may lead to skewed sex ratios (63)
Subpopulation characteristics	4.4 Changes in subpopulation age structure	Habitat/microhabitat changes	Altered resource availability likely shifts survival and reproduction and the age structure, e.g., in Arctic peregrine falcons (70)

Impact Category	Impact Metric	Potential Mechanisms	Arctic Example
Subpopulation characteristics	4.5 Changes in magnitude/frequency of subpopulation fluctuations	Habitat/microhabitat changes	Increased variability in local lemming cycles under warming scenarios (71)
Range characteristics (subpopulations)	5.1 Changes in range sizes of subpopulations	Habitat/microhabitat changes	Arctic char subpopulations now occupy smaller, isolated lakes due to glacial melt and habitat fragmentation (72)
Range characteristics (subpopulations)	5.2 Changes in range locations of subpopulations	Habitat/microhabitat changes	Geese subpopulations shift nesting sites as local breeding habitat quality changes (30)
Genetic characteristics (subpopulations)	6.1 Changes in genetic diversity	Habitat/microhabitat changes	Sea ice extent determines genetic diversity for Arctic foxes (73)
Genetic characteristics (subpopulations)	6.2 Changes in allele frequencies	Physiological misalignment with environmental conditions	Adaptive shifts in allele frequencies in fish in response to warming waters and heat stress (observed in the Mediterranean (68))
Genetic characteristics (subpopulations)	6.3 Changes in gene flow between subpopulations	Habitat/microhabitat changes	Gene flow between polar bear subpopulations from Hudson Bay and Kane Basin is reduced due to less sea ice (66)
Level: Individual			
Life-history characteristics	7.1 Changes in growth rates	Physiological misalignment with environmental conditions	Warmer water temperatures may alter growth rates in Arctic char (74)
Life-history characteristics	7.2 Changes in duration of developmental stages	Physiological misalignment with environmental conditions	Insects in the Arctic may exhibit faster developmental rates under warmer conditions (hypothetical)
Life-history characteristics	7.3 Changes in reproductive output and success	Physiological misalignment with environmental conditions; habitat/microhabitat changes	Narwhals may experience reduced reproductive output due to increased energetic costs from avoiding ice-free zones (75)
Life-history characteristics	7.4 Changes in survival rates and longevity	Physiological misalignment with environmental conditions; habitat/microhabitat changes	Polar bears in areas with severe sea-ice loss show reduced survival rates due to heightened stress and diminished habitat quality (69)
Morphological characteristics	8.1 Changes in body size	Habitat/microhabitat changes	Warming advances phytoplankton blooms, decoupling them from fish larval emergence, leading to food scarcity and smaller juvenile fish (76)
Morphological characteristics	8.2 Changes in body shape	Physiological misalignment with environmental conditions	Arctic char expresses in warmer waters a benthivorous rather than a pelagic phenotype (e.g., larger size) (77)

Impact Category	Impact Metric	Potential Mechanisms	Arctic Example
Physiological characteristics:	9.1 Changes in phenotypic plasticity	Physiological misalignment with environmental conditions	Arctic cod show plastic adjustments in metabolic responses under warming conditions (78)
Physiological characteristics	9.2 Changes in metabolic rate	Physiological misalignment with environmental conditions	In many marine species, the metabolic rate increases with temperature, while the availability of oxygen limits this increase (79)
Physiological characteristics	9.3 Changes in stress tolerance	Physiological misalignment with environmental conditions	Caribou facing increased predation risk in a warming landscape show elevated stress hormone levels (80)
Physiological characteristics	9.4 Changes in disease susceptibility	Physiological misalignment with environmental conditions	Warmer winter conditions favour higher parasite/tick loads in Arctic seabirds (81)
Phenological characteristics	10.1 Changes in seasonal timing	Phenological disruptions	Earlier sea-ice breakup has shifted the timing of beluga whale migrations (82)
Phenological characteristics	10.2 Changes in migration direction/distance	Phenological disruptions	Geese adjust their migration routes in response to changes in breeding ground conditions (83)
Phenological characteristics	10.3 Changes in circadian patterns	Phenological disruptions	Reindeer exhibit circadian rhythms due to extended summer daylight (84)
Genetic characteristics	11.1 Changes in gene expression	Physiological misalignment with environmental conditions	Hares remain brown during the winter in regions with low snow cover (85)
Genetic characteristics	11.2 Changes in heterozygosity	Habitat/microhabitat changes	Barents Sea polar bears experienced a 3–10% loss of genetic diversity and ~ 200% increase in genetic differentiation among subpopulations over two decades due to the loss of sea ice (86)

2.1.5. Adaptation mechanisms

We recorded all adaption descriptions (e.g., behaviour shifts, phenology, distribution). Following Folden 2019, we categorized these into five broad categories (Table 2):

Table 2. Categories of adaption mechanisms

Category	Definition
Phenotypic plasticity	Adjustments of phenotype in response to changing conditions
Dispersal ability	Movement (both intrinsically, through movement, and extrinsically, by overcoming physical barriers) to new habitats
Establishment ability	Establishment in new environments
Proliferation ability	Reproduction in new habitats is crucial for adaptation
Evolvability	Genetic change, through mechanisms like gene flow and short generation times to adapt to climate change

2.1.6. Overview of extracted data
Summary of the extracted data (Table 3).

Table 3. Overview of extracted data

Extracted data
Impacts of climate change (e.g., trends in reproduction, body conditions)
Mechanism, effects of climate change (detrimental, beneficial)
Climate variables triggering changes (e.g., sea ice extent, temperature, precipitation, vegetation shifts, salinity)
Direction of the association (positive or negative) between climate variables and population or species responses.
Adaptation mechanisms (e.g., shifts in behaviour, phenology, distribution)
Exposure to pressures, categorized as abiotic pressures, biotic pressures, human response pressures

2.2. Analytical approach

2.2.1. Identifying Mechanisms Driving Responses
To understand wildlife responses to climate change and explore associations between climate variables and across species, regions, and functional groups, we will eventually use Generalized Linear Mixed Models (GLMMs) or Bayesian models. Predictors will include taxa (e.g., birds, mammals, fish), the functional group (e.g., Arctic vs. boreal, herbivores vs. carnivores), region (e.g., Eastern vs. Western Greenland), and climate variables (e.g., temperature trends, sea ice extent). To account for hierarchical variability across species and populations, species and study sites will be included as random effects. Depending on the modelling framework, a spatial correlation term will be incorporated to control for spatial autocorrelation using spatial random effects, covariance structures, or smooth spatial terms. We use a binomial regression with impact (detrimental impacts, beneficial impacts) as the response variable. Bayesian models could further enhance the analysis by integrating prior knowledge and quantifying uncertainty through posterior distributions, offering more profound insights into relationships and variability. Variance partitioning will quantify the variance explained by predictors, while non-linear relationships will be explored using quadratic terms or splines. This part of the analysis is ongoing.

2.2.2. Adaptation Mechanisms
To evaluate how species respond to climate change, focusing on shifts in timing, behaviour, or distribution, we conducted a comparative analysis across taxa to identify patterns of adaptation. We aimed to identify functional traits associated with successful adaptation, such as fecundity, dispersal ability, and temperature tolerance. We differentiate between different types of adaption following Foden et al., 2019 (Table 4). We utilized non-linear modelling techniques, including quadratic terms and splines, to examine non-linear relationships between climate drivers and adaptive responses. This setup enables the identification of species and populations showing evidence of resilience or thriving under changing conditions to inform adaptive management strategies.

2.3. Quality assessment and missing data

2.3.1. Rules for quality assessment and rating
Our approach also includes information about uncertainties. Future projected declines will, for instance, often be accompanied by lower certainty than information about already observed declines. We were interested in punctual events, such as observed adaptations or sightings, so we did not include quality criteria. Moreover, we aimed to include observed as well as scenario analyses. We weigh risk classifications towards most certain information. Rules adapted from Thomas et al., 2011 (Table 4) were used to evaluate confidence to ensure clarity, quality, and consistency in assessments. In Table 5, the practical data assessment process is described by outlining the four steps: Evaluate confidence in

observed declines, link observed declines to climate change, weigh projected declines lower than observed declines, and assess model quality (Table 5, summary in Table 6).

Table 4. General rules for confidence ratings

Confidence Level	Criteria
Good confidence	Detailed, long-term survey data (e.g., monitoring over 20+ years at multiple locations, adjusted for variable effort). Models accurately predict observed changes (validated with independent data). Trends have a greater than two-thirds probability of falling within the specified category.
Medium confidence	Moderate survey data (e.g., shorter time spans, repeat surveys with variable effort). Models are validated by splitting data into training and testing sets, though they lack tests of predicted changes over time.
Low confidence	Limited or qualitative data (e.g., expert opinion, unadjusted surveys). Models are tested only against the data used to build them (i.e., no independent validation).
No confidence	No trend or change data are available. In such cases, proceed to subsequent stages of the analysis.

Table. 5 Steps of the quality assessment of the data

Step	Description	Key Considerations
Step I.A – Observed data	Evaluate confidence in observed declines. **Good:** Detailed, long-term, and consistent monitoring data. **Poor:** Qualitative or inconsistent trend data (e.g., variable effort or short-term observations).	Data quality, consistency, survey duration, and spatial/temporal coverage.
Step I.B – Climate change linkage	Link observed declines to climate change only if supported by evidence. Assessment confidence depends on the strength of evidence and whether alternative drivers (e.g., habitat destruction) have been considered.	Strength of causal evidence, identification of potential confounding factors, and the comprehensiveness of climate versus non-climate driver analysis.
Step II – Projected declines	Recognize that projected declines are weighted lower than observed declines due to inherent uncertainty. **Good:** Models accurately predict observed changes and are consistent across scenarios. **Medium:** Models validated using spatial data but not tested over time. **Low:** Models lack validation beyond their training data.	Robustness of model projections, uncertainty in scenario selection, and the extent of model validation (e.g., independent or cross-validation methods).
Step III – Weighting observed vs. projected declines	Observed declines are given greater weight when available. For nonlinear climate scenarios or species responses (e.g., accelerated warming), recast declines as percentage changes projected to 2050 or 2100.	Relative certainty between empirical data and model projections, treatment of nonlinear responses, and the rationale for weighting differences.
Step IV – Model quality and confidence	Assess model quality using established criteria: **Good:** Models accurately predict changes already observed over time and perform well across alternative scenarios. **Medium:** Models predict current distributions using separate training and testing data. **Low:** Models are tested only on the data used to build them.	Model validation method (independent data, cross-validation), performance metrics, consistency across alternative scenarios, and quantification of uncertainty.

Step	Description	Key Considerations
	For projections with uncertain climate links, assign Low Confidence unless strong evidence supports the link.	

Table 6. Summary of Rules

Rule Number	Summary
1	Prioritize observed declines over projections when available.
2	Confidence levels (Good, Medium, Low) depend on data quality, model validation, and the strength of evidence linking trends to climate change.
3	Weight information based on certainty—with detailed, long-term, and validated data receiving the highest weight.
4	If climate links are absent or unclear, proceed cautiously and assign lower confidence.

2.3.2. Missing data

We acknowledge that certain factors, such as research bias toward iconic species or the physical accessibility of populations, may lead to over- or under-reporting of effects for some populations. To address this, we standardize scores within each species by dividing by the maximum possible score for each species (87). This approach ensures missing scores do not influence the final outcomes (54).

2.4. Aggregation of Ratings

Given the various approaches available for combining ratings, the method we choose l depends on the distribution and characteristics of the data (54,58,59). Once the data distribution is clear, we will determine whether to use methods such as calculating the mean or median or applying multiplication or additive strategies. This ensures that the aggregation approach.

3. Results (preliminary)

We have completed extracting relevant literature and are currently extracting information from newly added sources. So far, we have listed 742 individual publications. Each publication can investigate multiple aspects and mechanisms. Until now, 895 pieces of evidence have been extracted from the data. The project's progress and current state can be accessed here. We aim to complete the literature research by 2025 to cover the climate extreme years 2023 and 2024, as they might severly influence the study outcomes. Currently, studies are only listed up to early 2024. Additionally, we will expand the dataset to include all literature at the population level. Until now, only Greenlandic sites, our initial research priority, have been listed at this level.

Boreal whales had the highest number of records, with 122, followed by Arctic whales (114), Arctic-boreal birds (94), terrestrial herbivores (94), ice seals (88), terrestrial carnivores (88), Arctic birds (87), Arctic fish (52), boreal birds (51), boreal fish (44), Arctic-boreal fish (32), and non-ice seals (29).

Geographically, the most researched countries in the dataset were Greenland (104 mentions), Canada (72 mentions), and Norway (57 mentions). Research efforts were concentrated in Arctic hotspots, with West Greenland (83 records) being the most studied region, followed by Svalbard (57 records), East Greenland (56 records), Iceland (23 records), and the Barents Sea (23 records).

Among individual species, polar bear (*Ursus maritimus*) had the highest recorded occurrences (71), followed by reindeer/caribou (*Rangifer tarandus*) with 58, narwhal (*Monodon monoceros*) with 56, thick-billed murre/Brunnich's guillemot (*Uria lomvia*) with 50, bowhead whale (*Balaena mysticetus*) with 36, ringed seal (*Pusa hispida*) with 34, muskoxen (*Ovibos moschatus*) with 34, common eider (*Somateria mollissima*) with 30, walrus (*Odobenus rosmarus*) with 29, and little auk (*Alle alle*) with 29 (Figure 1). The species with the least evidence (fewer than five occurrences) include lumpfish

(*Cyclopterus lumpus*, 3), thorny skate (*Amblyraja radiata*, 3), spotted wolffish (*Anarhichas minor*, 3), and blue whiting (*Gadus poutassou*, 4) and common loon (*Gavia immer*, 0) and common raven (*Corvus corax, 1*).

3.1. Broad aspects investigated

The grouping of the investigated aspects following Foden et al., 2019 (Table 1) into physiological, population, morphological, range, phenological, life-history, environmental, and genetic aspects showed that the category “Population characteristics” accounted for 55.08% of all categorized entries, indicating a strong focus on understanding species’ population trends, distribution, and dynamics (Figure 1). The second most frequent category is “Range characteristics,” comprising 16.86% of the dataset, highlighting an emphasis on species’ geographical distribution and shifts. “Life-history characteristics” follow at 10.74%, demonstrating an interest in species reproductive and survival strategies. Conversely, “Phenological characteristics” (4.62%) and “Environmental characteristics” (4.50%) are less represented, indicating fewer studies on seasonal timing and habitat-related aspects.

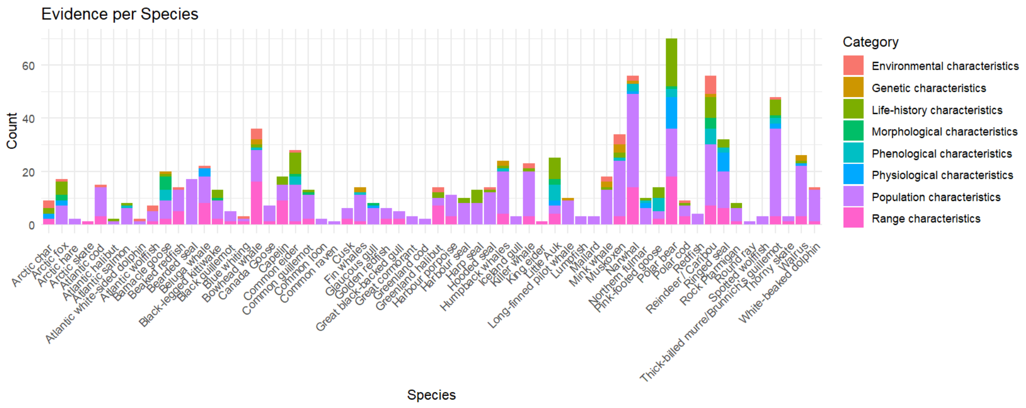

Figure 1 Type of evidence per species, categorized into physiological, population, morphological, range, phenological, life-history, environmental, and genetic aspects (54).

The analysis of categories within animal groups revealed that Arctic fish have a strong representation in “Range characteristics” (40.38%) and “Population characteristics” (28.85%), indicating that studies on these species focus mainly on their distribution and population dynamics (Figure 2). Arctic whales exhibit similar trends, with “Population characteristics” making up 50.00% of the category representation, followed by “Range characteristics” at 33.33%. Arctic-boreal fish, however, show the highest focus on “Population characteristics” (65.63%), suggesting intensive monitoring of their population trends. For birds, Arctic birds have 51.85% of their studies categorized under “Population characteristics” and 8.64% under “Range characteristics,” whereas Arctic-boreal birds have 49.41% in “Population characteristics” and 9.41% in “Range characteristics.”

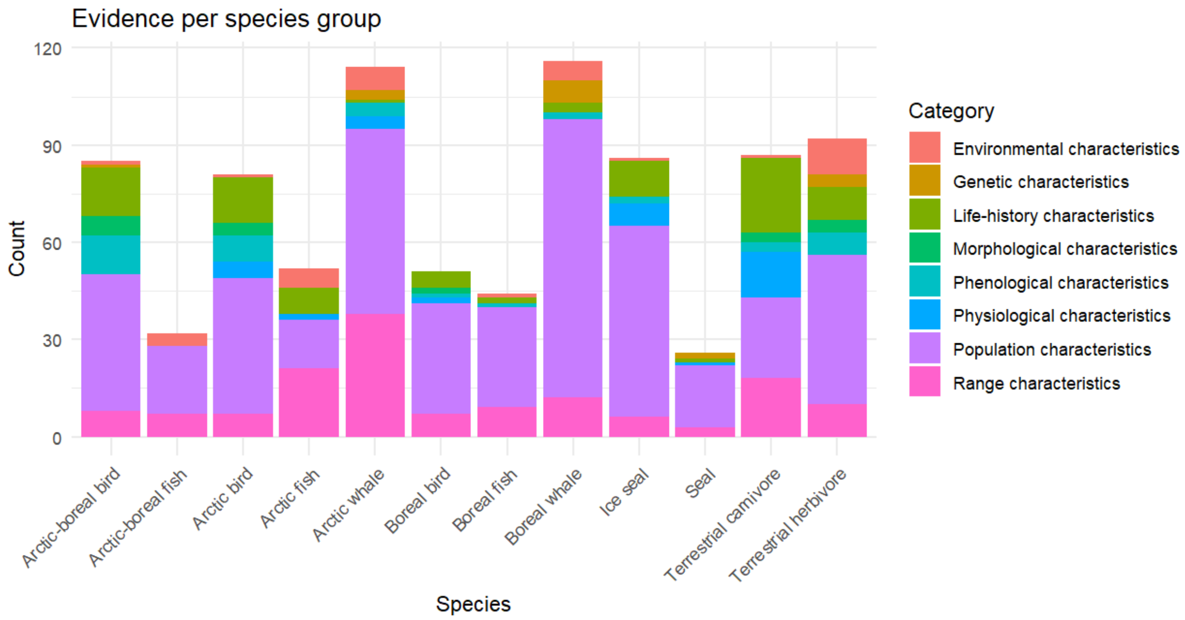

Figure 2. Type of evidence categorized into physiological, population, morphological, range, phenological, life-history, environmental, and genetic aspects (54) per species group.

3.2. Categories of explanatory variables

We mapped the explanatory variables into categories: sea surface temperature (SST), climate oscillation indices, sea ice dynamics, phenological shifts, body condition and physiology, pollution and contaminants, extreme events, trophic interactions, habitat and ecosystem shifts, and temporal and spatial trends (Figure 3). Further explanation of the mapping process can be found in Table 7 in the Appendix.

The analysis of explanatory variables across species groups highlights distinct patterns in the environmental and climatic factors investigated and found to influence these taxa. Arctic birds were most frequently associated with sea surface temperature (SST) (22 occurrences, 31% of all explanatory variables recorded for this group), followed by sea ice dynamics (13, 18%) and climate oscillation indices (9, 13%). Trophic interactions, oceanography, and chemistry received less emphasis (5 and 4 occurrences, respectively). Arctic fish studies also frequently reported SST (8, 27%) and sea ice dynamics (5, 17%) but showed a relatively stronger focus on oceanography and chemistry (4, 13%), indicating an emphasis on the role of water chemistry and nutrient cycles in determining habitat suitability. For Arctic whales, the most common explanatory variable was temporal and spatial trends (16, 36%), followed by SST (9, 20%) and habitat and ecosystem shifts (7, 16%). Arctic-boreal birds, which occupy transitional habitats, showed a different emphasis, with phenological shifts (14, 16%) and hydrology and precipitation (8, 9%) among the most investigated factors, along with SST (28, 31%) and climate oscillation indices (18, 20%). Boreal birds and boreal fish exhibited distinct patterns. Boreal birds mainly were associated with SST (5, 28%) and climate oscillation indices (4, 22%). In contrast, boreal fish had the strongest association with oceanography and chemistry (11, 37%) and SST (8, 27%). Ice seals showed the strongest link to sea ice dynamics (14, 39%), followed by oceanography and chemistry (8, 22%). Terrestrial carnivores, such as polar bears (*Ursus marinus*), were overwhelmingly linked to sea ice dynamics (28, 52%), highlighting their reliance on ice-covered habitats. Temporal and spatial trends (9, 17%) were the next most frequently investigated factor, emphasizing the importance of habitat fragmentation and changing prey distributions. Terrestrial herbivores, including muskoxen (*Ovibos moschatus*) and caribou (*Rangifer tarandus*), were primarily associated with demographics and species traits (11, 20%), hydrology and precipitation (11, 20%), and snow and cryosphere (7, 13%).

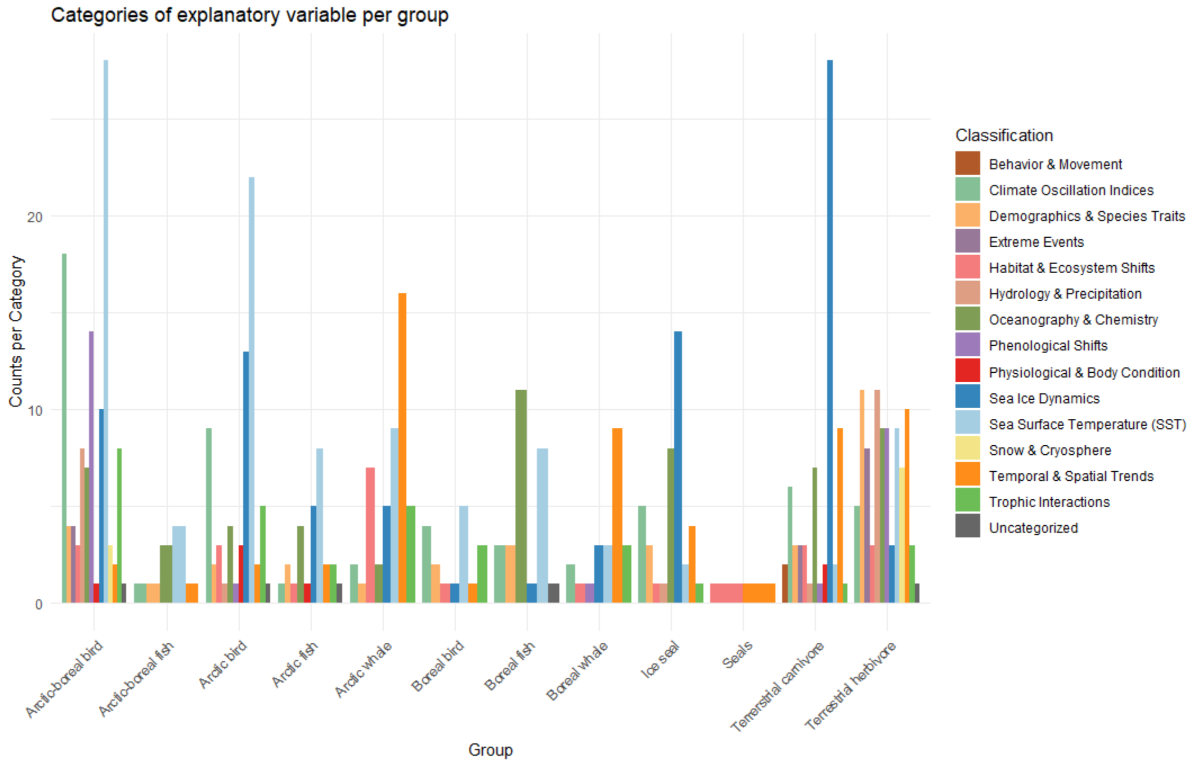

Figure 3. Investigated explanatory variables per group

3.3. Categories of response variables

We mapped the response categories that were investigated in relation to climate and trend developments into categories (Figure 4). This included habitat and environment, future habitat projections, feeding ecology, future range projections, future trend projections, future migration, future reproduction, population trend, population dynamics, breeding and reproduction, predation, migration, behaviour, range/space use, physiology and morphology, sea ice entrapments, catch data, population status, survival, stranding events, rain on snow events, (inter)species interactions, parasites and diseases, pollution and contaminants, human-wildlife conflict, resource pressure and competition, and population genetics. For further description of the mapping, see Table 8 in the Appendix. The most frequently studied response category was population trend, representing 38.4 percent of all cases. Across species and species groups, for boreal whales were the highest focus on population trend, accounting for 20.1 percent of all cases, followed by Arctic whales at 13.7 percent and terrestrial herbivores at 10.5 percent (Figure 5).

At the species level, the most frequently studied taxa within population trend were narwhal, representing 8.4 percent of cases, Thick-billed murre or Brünnich's guillemot at 7.6 percent, and reindeer or caribou at 5.5 percent. Species with no recorded population trend data include king eider (*Somateria spectabilis*), Arctic skate (*Amblyraja hyperborea*), Arctic char (*Salvelinus alpinus*), Atlantic halibut (*Hippoglossus hippoglossus*), and lumpfish.

For other species, there was also little evidence for trend data, such as little auk (*Alle alle*), black guillemot (*Cepphus grylle*), Canada goose (*Branta canadensis*), pink-footed goose (*Anser brachyrhynchus*), and Common raven.

It is important to note that the presence of trend data as a category does not necessarily indicate that reliable trend data are available. Sometimes, the trends may still be unknown or of limited quality.

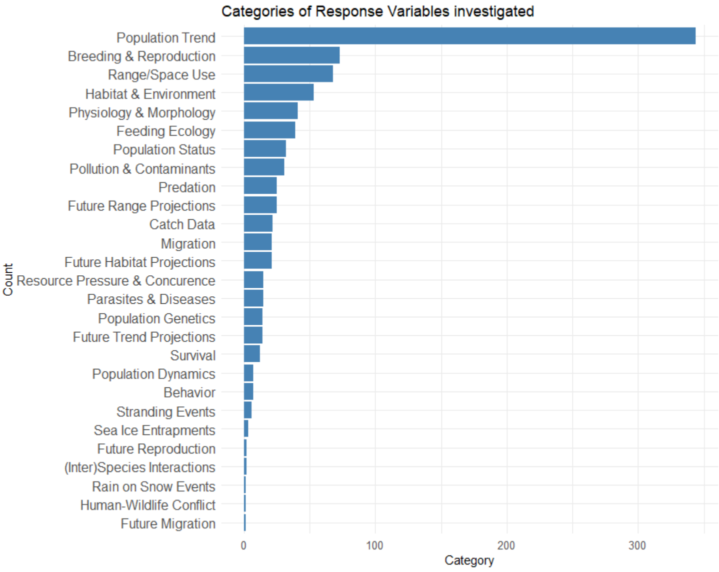

Figure 4. Counts of investigated response categories

Breeding and reproduction were also a major area of study, representing 8.2 percent of cases (Figure 4). Among groups, birds had the highest representation in breeding and reproduction research, particularly seabirds and waterfowl species. Terrestrial herbivores, including reindeer and caribou, also had a notable proportion of studies related to reproductive success and breeding patterns. The species most frequently studied in this category were reindeer or caribou, which accounted for 15.1 percent of all breeding and reproduction studies. Little auk followed with 11.0 percent, while common eider and Polar bear each represented 9.6 percent. Barnacle goose was also frequently studied, making up 8.2 percent of cases.

Other commonly studied categories included range/space use at 7.6 percent. Range and space use was a significant research focus for various Arctic species. Among groups, marine mammals and fish had the highest representation in range and space use research (Figure 5). The species most frequently studied in this category were polar bears, and capelin (*Mallotus villosus*) accounted for 8.8 percent of all studies related to range and movement. Killer whales (*Orcinus orca*) followed with 7.4 percent, while beaked redfish (*Sebastes mentella*) and humpback whales (*Megaptera novaeangliae*) each represented 4.4 percent.

The habitat and environment category was studied in 5.9 percent of all cases, making it a moderately represented research focus. Among taxonomic groups, marine mammals and fish had the highest representation in habitat and environment studies (Figure 5). The most frequently studied species in this category were narwhal (*Monodon monoceros*), bowhead whale (*Balaena mysticetus*), beluga whale (*Delphinapterus leucas*), Greenland halibut (*Reinhardtius hippoglossoides*), and humpback whales (*Megaptera novaeangliae*).

Physiology and morphology was investigated by 4.6 percent, primarily conducted on Arctic fish, which accounted for 72.7 percent of studies within their group (Figure 5). Feeding ecology accounted for 4.36 percent and among taxonomic groups. Here, Arctic birds were the most studied for feeding ecology, making up 30.2 percent of studies in this category, followed by Arctic fish at 28.3 percent and marine mammals at 22.6 percent. Feeding ecology research was most frequently conducted on thick-billed murre, which accounted for 18.9 percent of all feeding ecology studies, followed by Atlantic cod (*Gadus morhua*) accounted for 16.2 percent, while for Arctic char (*Salvelinus alpinus*) 10.8 percent of studies investigated feeding aspects.

Future-oriented studies, such as future range, trend, and habitat projections, collectively represented 8.2 percent of all cases, indicating a relatively limited focus on predictive modelling of Arctic species responses to environmental changes. Future-oriented studies were most frequently conducted on bowhead whales, accounting for 13.3 percent of all such studies (Figure 4). Narwhals followed with 11.7 percent, while Atlantic cod and beluga whales each represented 8.3 percent. Polar bears were also notable, making up 5.0 percent of future-related research.

The analysis of species research related to the accumulation of pollutants and contaminants in their bodies reveals notable trends in the focus of Arctic and sub-Arctic ecological studies. Among the species studied, the ringed seal (7 studies, 28%) and the polar bear (7 studies, 28%) emerged as the most frequently investigated species for pollution-related effects. In addition to these apex species, Arctic foxes (3 studies, 12%) and beluga whales (3 studies, 12%) were also prominently investigated. Lesser-studied species, such as the little auk (2 studies, 8%)**,** represent a focus on avian populations, though birds overall appear underrepresented compared to mammals.

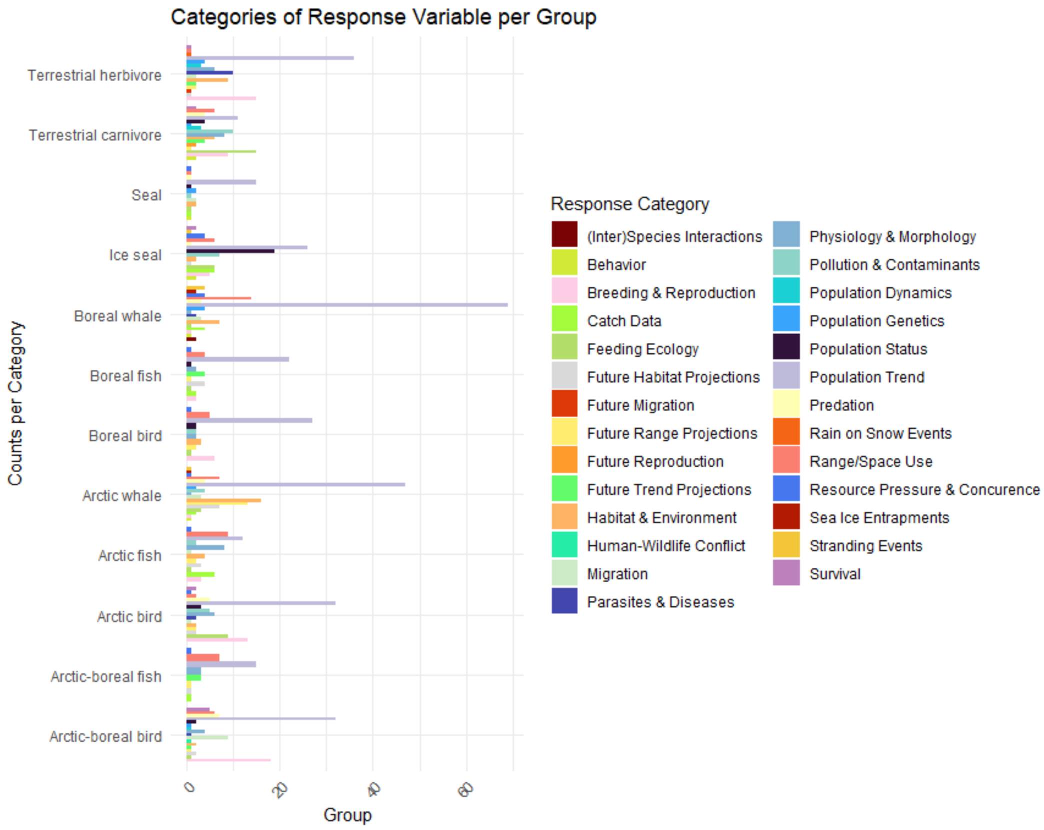

Figure 5. Investigated response categories per animal group.

The modelling part of the analysis is still ongoing.

4. Discussion

This study provides a comprehensive synthesis of Arctic wildlife research, compiling and analyzing 742 publications and 895 pieces of evidence on species' responses to environmental changes on the population, subpopulation or species level. The dataset highlights boreal whales and Arctic whales, especially species like narwhal, Arctic-boreal birds with thick-billed murre, terrestrial herbivores, with species such as reindeer and terrestrial carnivores, especially polar bears, as research priorities. Other species, such as lumpfish, thorny skate, and spotted wolffish, had limited representation. Research concentrated in Arctic hotspots such as Greenland, Canada, and Norway and focussed on population characteristics, range characteristics, and life-history traits, with population trends being the most frequently studied response variable and key environmental factors including sea surface temperature, sea ice dynamics, and climate oscillation indices. However, knowledge gaps remain, as physiological responses, phenological shifts, and long-term trend projections are underrepresented, and several species, such as king eider, Arctic char, and lumpfish, lack recorded trend data. Additionally, future-oriented studies are scarce, restricting predictive insights into Arctic species' responses to climate change, while pollution and contaminant accumulation research primarily focus on ringed seals and polar bears, leaving gaps in understanding the effects on other species.

4.1. Evidence per species group and species

The findings reveal a strong research focus on population characteristics, which dominate the dataset, emphasizing the importance of understanding species' population trends, distribution, and dynamics. This finding aligns with conservation and management priorities, as tracking population trends is essential for assessing species' responses to environmental change and exploitation. Range characteristics are the second most studied category, underscoring the need to monitor geographical shifts in response to climate change. These studies primarily focus on birds and marine mammals, reflecting their high mobility and sensitivity to environmental changes.

Despite this focus, life-history traits receive comparatively less attention, while phenological and environmental characteristics are even more underrepresented. This finding highlights research gaps, as shifts in phenology, such as changes in breeding or migration timing, and habitat alterations are critical indicators of ecological responses to climate change. Reproductive studies are more prevalent in Arctic fish and terrestrial herbivores, likely due to the influence of seasonal food availability and breeding conditions. Body condition and survival studies are more common in terrestrial carnivores and herbivores, emphasizing the direct effects of climate variability on fitness and foraging success.

Research focus varies across taxonomic groups. Studies on Arctic fish predominantly examine range and population dynamics due to their economic and ecological significance. Research on Arctic whales emphasizes population characteristics and range shifts, reflecting concerns about their conservation status and changing Arctic ecosystems. Arctic-boreal fish show the highest focus on population characteristics, highlighting intensive monitoring efforts. For birds, both Arctic and Arctic-boreal species are primarily studied in terms of population characteristics, with less attention given to range dynamics.

Furthermore, the distribution of species investigated is biased towards certain species that receive disproportionately high research attention while others remain understudied. Large iconic species or commercially important species, such as polar bears or boreal and Arctic whales, as well as terrestrial herbivores like caribou, are extensively examined. In contrast, smaller or less economically significant species, such as lumpfish, thorny skate, and spotted wolffish, have limited representation. The frequent focus on ice-dependent seals further underscores the heightened vulnerability to the disruption of sea ice ecosystems and its cascading effects on species that rely on ice for breeding and foraging (34). Although bias in biomonitoring is a global phenomenon (88), this uneven distribution may lead to knowledge gaps in understanding ecosystem-wide responses to climate change, particularly for species that play critical roles in food webs but receive less direct research attention. Addressing this imbalance by expanding research efforts to underrepresented species and ecological aspects will be essential for a more comprehensive understanding of Arctic biodiversity and its resilience to environmental change.

4.2. Explanatory categories in relation to species and species group

Marine and ice-dependent groups, like Arctic birds, fish, and whales, frequently exhibited links to SST and sea ice dynamics, reinforcing the well-documented impact of Arctic warming and ice loss on these groups. For instance, sea ice dynamics accounted for 18% of explanatory variables in Arctic birds, 17% in Arctic fish, and 39% in ice seals, all of which depend on ice-associated prey or breeding sites (34). Terrestrial carnivores, especially polar bears, had the highest relative focus on sea ice dynamics (52%), emphasizing their direct dependence on stable ice habitats (63,66).

Climate oscillation indices, such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Subpolar Gyre Index (SPG), were frequently studied in Arctic-boreal birds (20%) and boreal birds (22%), as well as in Arctic fish (13%). These findings suggest that large-scale atmospheric and oceanic circulation patterns strongly influence species distributions, seasonal migration, and food availability (89–91). For example, fluctuations in circumpolar seabird populations are linked to climate oscillations (91). Arctic-boreal birds, in particular, showed a strong link to phenological shifts (16%), which highlights the importance of seasonal timing mismatches between food availability and breeding. Geese, in particular, are rapidly shifting their migration routes, adjusting them to the onset of spring and food availability during their migration (30,49).

Terrestrial herbivores were uniquely associated with hydrology and precipitation (20%) and snow and cryosphere (13%), suggesting that water availability and winter snow depth are key constraints on their distribution and fitness. Especially rainy and warmer winters, paired with rain on snow events that are icing feeding grounds, can decrease winter survival in Arctic ungulates (92,93). In contrast, marine groups were predominantly linked to oceanographic factors (22% in ice seals, 37% in boreal fish) and SST (31% in Arctic birds), which regulate primary reproduction and prey abundance (26,94,95).

Boreal fish had the highest proportion of studies linked to oceanography and chemistry (37%), highlighting the importance of freshwater nutrient dynamics and threats like ocean acidification and oxygen saturation. Boreal bird studies focused on SST (28%) and climate oscillation indices (22%), which are important indicators for food availability and ecological shifts favouring boreal species (26,94,95). Boreal whales strongly emphasised temporal and spatial trends (9 occurrences, 39%), reflecting changing prey distributions and their influx into Arctic waters due to warming waters and less sea ice (26).

Overall, the observed effects of explanatory variables highlight climate and habitat changes as predominant stressors for Arctic and boreal species. Marine species, particularly those reliant on ice-covered habitats, are heavily impacted by warming temperatures and declining sea ice, while terrestrial herbivores face increasing pressure from altered precipitation patterns and snow cover changes. These findings reflect patterns derived from the literature and may be influenced by research biases. For instance, the high occurrence of SST and sea ice dynamics in Arctic species groups could result from extensive climate change monitoring in marine environments. In contrast, physiological and body conditions received relatively little emphasis despite their potential importance in understanding adaptive responses to environmental stressors. Future studies should incorporate multi-scale ecological data to validate observed trends and assess species-specific vulnerabilities in greater detail.

4.3. Response categories concerning species and species group

The dominance of population trend as the primary response category suggests that research priorities in the Arctic are primarily focused on species abundance and population changes over time. This focus aligns with broader conservation concerns, as population declines serve as early indicators of environmental stress and habitat disruption.

The strong focus on whale populations, particularly boreal and Arctic whales, may be attributed to their sensitivity to shifting sea ice conditions, prey availability, and human activities such as shipping and fishing (75,96). The expansion of many boreal whale species into Arctic waters, such as killer whales establishing themselves as new apex predators, and the cascading effects on Arctic food chains and behavioural changes within native Arctic species are frequently studied to gain insights into shifting ecosystem dynamics (33,36). Similarly, the significant representation of terrestrial herbivores like reindeer and caribou reflects growing concerns over habitat loss, changing vegetation, and extreme weather events such as rain on snow events, affecting grazing conditions and, ultimately long-term survival (92).

The high number of studies on narwhals and thick-billed murres or Brünnich’s guillemots under population trend suggests a multi-trophic approach in Arctic research. As top marine predators, these species are important bioindicators of ecosystem health, making them valuable targets for monitoring climate-driven changes in Arctic biodiversity (97,98). Most colonies show declining trends, further exacerbated by emerging threats such as increased predation by polar bears (99,100). The strong emphasis on breeding and reproduction in species such as reindeer, little auk, and common eider suggests that reproductive success is a key focus in Arctic research, as they can be important indicators for long-term trends and survival and adaption to climate change (31,101). Moreover, the availability of resources at many breeding sites is changing because of climate change (101,102). Reindeer and caribou are likely studied due to their ecological importance and reliance on seasonal breeding cycles, which can be disrupted by climate change and habitat alterations, creating trophic mismatches (103). The high representation of seabirds and waterfowl, including little auk and common eider, may reflect concerns about nesting success, food availability, and environmental stressors affecting breeding outcomes. Using trend data and phenological changes, seabirds can be used as good qualitative indicators to observe the effects of climate change on food changes (104). Little auks are key ecological indicators of Arctic climate and oceanographic changes driven by Arctic amplification (105). Additionally, they are valuable models for studying ecosystem energy flow, mate choice, parental care, and biological rhythms (105).

Polar bears also ranked highly in this category, highlighting the interest in their reproductive success as an indicator of broader Arctic ecosystem health. Since polar bears depend on stable sea ice for mating and denning, climate-driven ice loss may be a critical factor influencing their breeding patterns (106). Reproductive success data are often used alongside or as a substitute for trend data to assess the health of a subpopulation and the effects of climate change (107).

The strong focus on range and space use in marine mammals and fish suggests that researchers are particularly interested in how climate change and environmental variability affect species distributions. As a key Arctic predator, polar bears rely on sea ice for movement and hunting, making this species critical for studying climate-driven habitat changes (66). Similarly, killer and humpback whales are highly mobile species whose range expansions may be influenced by shifting prey distributions and warming waters (26).

Capelin and beaked redfish are key prey species, with changes in their movement and distribution potentially causing cascading effects on Arctic marine food webs. Capelin is a keystone forage species, serving as a vital food source for seals, whales, larger fish predators, and the fishery, with significant direct and indirect impacts on the fishing industry (38,108,109). Including these species in range and space-use studies underscores the importance of monitoring habitat shifts across multiple trophic levels. Overall, the findings indicate that range and space use research concentrates on species with high mobility and ecological or economic significance.

The strong presence of Arctic birds in feeding ecology research highlights interest in how these species interact with food resources and shifting prey availability. Thick-billed murre was this category's most frequently studied species, reflecting concerns about how environmental changes impact seabird foraging success. The presence of Atlantic cod and Arctic char in this category suggests a research focus on their role as key prey species in Arctic and boreal ecosystems (74,110). Moreover, Atlantic cod is a valuable species for the fishing industry that prefers cold and shallow habitats, environments highly vulnerable to rapid climate change, making it an important climate change indicator (110,111).

Physiology and morphology research was highly concentrated on Arctic fish, indicating strong interest in their physiological adaptations to cold environments and food availability. Arctic char especially shows the variability of adaption towards climate change, such as the expression of a benthivorous rather than a pelagic phenotype in warmer waters with larger individuals (77). Arctic-boreal birds had significant representation in this category, highlighting research on the effects of climate change on breeding outcomes and effects in extreme environments (112,113). Including boreal fish in this category suggests a focus on their ability to tolerate temperature fluctuations and their ability to move northwards into Arctic territories (114).

The limited focus on feeding ecology studies for marine mammals suggests that research concentrates more on birds and fish than large predators. This may be due to birds' greater dietary flexibility, quicker responses to environmental changes, and their role as environmental sentinels for broader ecosystem shifts that ultimately affect marine mammals (104,105). Future studies should explore how changes in prey availability directly impact higher trophic levels, such as seals and whales.

Ringed seals and polar bears emerged as the most frequently studied species for pollution-related effects, reflecting their roles as critical indicators of pollutant bioaccumulation and biomagnification in Arctic food webs. As apex predators, ringed seals and polar bears are particularly vulnerable to persistent organic pollutants (POPs) and heavy metals such as mercury, which accumulate as they ascend trophic levels. Their long lifespans and high trophic positions exacerbate their susceptibility to bioaccumulation, making them critical for understanding trophic-level impacts and pollutant biomagnification (41,115). Climate change is disrupting Arctic food webs and accelerating sea ice melting, increasing pollutants and heavy metals in the environment, further compounding its effects on these species and the ecosystems they inhabit (116–118). However, the relatively low representation of avian species and certain marine mammals suggests gaps in current knowledge. Expanding research to include more species across trophic levels and habitats would provide a more comprehensive understanding of pollutant pathways and their ecological impacts.

Future-focused studies, comprising only 8.2% of the dataset, indicate growing but limited efforts to predict changes in species distribution, habitat availability, and population trends. While retrospective monitoring dominates, research must be expanded into climate impact projections and long-term conservation planning. Increasing efforts in future range, trends, and habitat predictions could offer critical insights for proactive conservation strategies. The emphasis on large marine mammals, such as bowhead and beluga whales, reflects a strong interest in understanding how declining sea ice will affect their habitats, migration patterns and feeding grounds (119,120). Similarly, including Atlantic cod highlights concerns about the impacts of warming waters and changing ocean conditions on commercially and ecologically significant fish species (110). Research on the potential future of polar bears encompasses already two decades of research and a range of methods that aim to understand the effects of ice loss and habitat fragmentation on their survival (60,121). These findings suggest that predictive research is increasingly used to anticipate climate change impacts on Arctic wildlife. Expanding these studies to include additional species and integrating long-term ecological data with climate models could enhance conservation planning and mitigation strategies.

5. Conclusion

The association between species groups and research categories reflects distinct ecological pressures within Arctic ecosystems. Marine mammals and birds are predominantly studied in relation to range shifts and migration due to their reliance on environmental cues such as ice cover and seasonal food availability. In contrast, terrestrial herbivores and carnivores are primarily studied in terms of survival and body condition, highlighting the direct physiological challenges they face from changes in snow cover, vegetation availability, and temperature extremes. These differences in research focus underscore the need for targeted approaches to studying and conserving Arctic species based on their ecological roles and vulnerabilities.

The findings emphasize the critical need for long-term monitoring and a comprehensive, integrative research approach that addresses multiple stressors, including climate change, pollution, and habitat loss. Population monitoring remains a dominant focus across Arctic species, particularly in marine and terrestrial mammals. However, future studies should aim to fill gaps in geographical coverage and explore the interactions between environmental pressures, such as how pollution and climate change impact food webs. Additionally, assessing how research priorities have evolved could reveal shifts toward species or groups increasingly affected by accelerating climate change.

Future conservation strategies must focus on mitigating carbon emissions, reducing habitat fragmentation, and maintaining critical habitats. Stabilizing sea ice for marine mammals and preserving seasonal snow cover for terrestrial species will be essential to supporting the resilience of Arctic ecosystems. Expanding research to understand species' responses to environmental changes at multiple trophic levels will also help inform holistic conservation planning.

By aligning research efforts with proactive, adaptive conservation strategies, the scientific community can better address the interconnected challenges posed by a rapidly changing Arctic. These efforts will be essential for ensuring the long-term sustainability of Arctic and boreal ecosystems in the face of ongoing environmental pressures.

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Appendix

Table 7 Categories of explanatory variables and their description

Category	Description
Sea Surface Temperature (SST)	Includes references to sea surface temperature changes and variations.
Climate Oscillation Indices	Covers major climate indices such as Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Subpolar Gyre (SPG).
Sea Ice Dynamics	Examines changes in sea ice extent, cover, break-up, ice-free conditions, and haul-out areas.
Phenological Shifts	Focuses on seasonal timing changes such as spring onset, early snowmelt, freeze-up, and laying date shifts.
Body Condition & Physiology	Includes factors related to body condition, wet weight, energetic value, growth rate, metabolism, and stress responses.
Pollution & Contaminants	Investigates environmental pollutants, including mercury (Hg), PCBs, and plastics.
Extreme Events	Covers extreme climatic events like rain-on-snow (ROS), cyclones, and other severe weather occurrences.
Trophic Interactions	Studies interactions between species, including predation, competition, and key prey species like herring and capelin.
Habitat & Ecosystem Shifts	Explores landscape and ecosystem changes such as shrubbification, permafrost thawing, and atlantification.
Temporal & Spatial Trends	Analyzes long-term trends in species range shifts, gene flow, and climate projections based on RCP and SSP scenarios.

Table 8 Categories and description for response categories

Category	**Description**
Habitat & Environment	Studies on habitat selection, suitability, seasonal use, and environmental influences.
Future Habitat Projections	Predictions on habitat changes due to climate change, including suitability shifts.
Feeding Ecology	Research on foraging behavior, diet composition, and energy balance.
Future Range Projections	Projections of species distribution changes, including seasonal shifts.
Future Trend Projections	Forecasting population trends, including future abundance and biomass.
Future Migration	Modeling potential changes in migration patterns.
Future Reproduction	Predictions on reproductive success, breeding performance, and shifts.
Population Trend	Analysis of population changes, growth, abundance, and biomass fluctuations.
Population Dynamics	Studies on structure, density, seasonal fluctuations, and demographics.
Breeding & Reproduction	Research on breeding success, parental care, and offspring survival.
Predation	Studies on predator-prey interactions, predation risks, and pressure.
Migration	Investigations into migration timing, patterns, and habitat shifts.
Behavior	General behavioral studies outside of migration and feeding.
Range/Space Use	Research on species distribution, home range, and spatial ecology.
Physiology & Morphology	Studies on body condition, growth, morphology, and physiological adaptations.
Sea Ice Entrapments	Research on species affected by sea ice entrapment and movement constraints.

Catch Data	Studies using fishery data, CPUE (catch per unit effort), and spawning trends.
Population Status	Research on population viability, extirpation risk, and colony size trends.
Survival	Studies on factors affecting individual and population survival rates.
Stranding Events	Analysis of marine mammal strandings, including mass strandings.
Rain on Snow Events	Studies on the effects of rain-on-snow (ROS) events on Arctic species.
(Inter)Species Interactions	Research on ecological relationships, competition, and species interactions.
Parasites & Diseases	Studies on parasite prevalence, disease transmission, and health impacts.
Pollution & Contaminants	Research on pollutant accumulation, contamination risks, and toxicology.
Human-Wildlife Conflict	Studies on interactions and conflicts between human activities and wildlife.
Resource Pressure & Competition	Research on food competition, resource availability, and habitat pressure.
Population Genetics	Studies on genetic diversity, phylogeography, and genomic adaptations.