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## Original Research Paper

# Physiological and Behavioural Plasticity of Arctic Marine Vertebrates Facing Rapid Sea Ice Habitat Transformation

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**Key Words**

Arctic marine vertebrates, Sea ice loss, Physiological plasticity, Behavioural adaptation, Climate change, Ecosystem resilience.

**Abstract**

The rate of Arctic Warming has intensified the meltdown of the sea ice and basically altered the makeup, size, and seasonal trends of the marine ecosystems. Sea ice is also strongly linked to arctic oceanic vertebrates, including mammals, seabirds, and fish, to forage, breed, migrate, and evade predation, and therefore are very vulnerable to such modifications. The paper is a review of the available knowledge regarding the physiological and behavioral plasticity that allows the Arctic marine vertebrates to cope with the rapid alteration in sea ice environments. This study considers major physiological transitions, such as metabolic plasticity, thermoregulatory responses, endocrinology of stress, energy redistribution to favor survival in novel thermal environments, and prey dispersion. At the same time, it also studies the behaviour changes, including a shift in timing and route of migration, and diving and foraging behaviour, a change in preference and reliance on pelagic or coastal systems as ice-related niches are exploited. Though plasticity may provide a temporary cushion against environmental change, this study demonstrates its limits, especially when the melting rate of sea ice is more than the capacity of acclimating or when behavioral change increases the cost of acclimating and the number of human-wildlife interactions. The adaptive potential depends on species-specific differences in life history, trophic position, and sea ice dependence, which causes uneven tax-specific resilience. Another aspect that the paper addresses is the long-term sustainability, in terms of the vertebrate populations of the sea, of the Arctic marine ecosystems that endure cumulative stressors, i.e., ocean warming, prey redistribution, and anthropogenic disturbance. Physiological and behavioral plasticity are vital technologies and constraints essential to promoting predictive systems and to sustain conservation and ecosystem-led management of a swifter-shifting Arctic seascape.

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## Introduction

The changes in the Arctic environment are the most significant ones in history, and the rates of warming are occurring (Kuletz et al., 2024). It possesses a climate change, providing it with a scientific basis of predictive modelling and decision making in conservation, more than two times that of the world average (Lin, 2024). The other most evident and ecologically significant effects of such a rapid warming are the reduction in the area of sea ice, its depth, and its seasonal tolerance. Sea ice is one of the peculiarities of the marine Arctic ecosystem that structures the availability of habitat, primary productivity, and trophic relationships. With arctic marine vertebrates, e.g., mammals, seabirds, and fish, sea ice is not merely a physical habitat but also a feeding, breeding, resting, and predator avoidance platform (Grémillet & Descamps, 2023; Sabitkhanovich et al., 2025). Quick alternation of environment using sea ice, therefore, introduces great difficulties to the existence and survival of the species (West et al., 2023).

Life-history adaptations of the sea vertebrates in the Arctic have been closely related to the expected ice dynamics (Bestley et al., 2020; Shuert et al., 2022). The accelerating rate of melting of the sea ice is interfering with these ecological relationships, which have long-term existence. Reduced ice cover alters prey distributions, increases their exposure to the open water, and alters migration patterns, thereby imposing novel physiological and behavioral strains on the populations of the sea-dwelling vertebrates (Grunst et al., 2023). Response of these organisms to these pressures should be understood so as to assess the capacity of these organisms to adapt to the current climatic conditions that are characterized by change (Wernberg et al., 2025; Blanchet et al., 2020).

The physiological and behavioral plasticity, i.e., the ability of organisms to adapt their internal and external behaviours in response to changes in the environment, has emerged to be one of the most important processes that enable short-term persistence in a quickly changing environment (Duncan et al., 2024; Brandt et al., 2023). Physiological plasticity in the Arctic can include metabolic, thermoregulatory, stress responsiveness, resource distribution, and behavioral plasticity, which may include the timing of migration, foraging behaviour, diving behaviour, and habitat use (Orgeret et al., 2022; Fraser et al., 2023). These reactions might shield individuals from the instantaneous strain of the setting, but not without energetic and ecological costs (Grunst et al., 2023; Blondin et al., 2022).

Despite growing evidence on the Arctic climatic impacts, not many studies have been done on the combination of sea ice processes with physiological and behavioral processes of various vertebrate taxa. This paper aims to bridge that gap by analyzing the use of plastic responses to cope with the rapidly changing habitat by the arctic marine vertebrates, evaluating the efficiency and constraints of the adaptations, and discussing their implications for long-term population stability and conservation in the rapidly changing arctic ecosystem.

The primary objective of the provided research is to discover how marine vertebrates in the Arctic respond to the swift alteration of the sea ice habitat through physiological and behavioral plasticity. More specifically, the research will establish the impacts of changes in sea ice dynamics on metabolic control, stress physiology, body status, movement patterns, foraging behaviors, and habitat selection in a number of taxa of vertebrates. With a combination of environmental, behavioral, and physiological records, the study is focused on the identification of species and cross-taxa design of adaptive flexibility, the boundaries beyond which the plastic responses can be insufficient or maladaptive. Lastly, knowledge regarding adaptive abilities will be increased, along with the vulnerability of the Arctic Sea vertebrates in accelerated conditions.

### Key Contribution

- Provides a collective analysis of both physiological and behavioral plasticity of the Arctic marine vertebrates in the rapid loss of sea ice.
- Establishes quantitative relationships between the processes of the sea ice and organism-level responses using remote sensing, biologging, and biological indicators.
- Identifies species-specific adaptive abilities between ice-obligate and ice-associated vertebrates.
- Refers to stressed-out and trophic active and passive trade-offs in the context of behavioral flexibility in increasingly ice-free environments.
- Offers empirical data on the limitations of plasticity in the face of a fast-changing climate, and informs climate-sensitive conservation and ecosystem-wide management instruments in the Arctic.

Section I (Introduction) describes arctic warming, sea ice processes, and ecological implications. Section II (Materials and Methods) describes the study regions, species selection, environmental and behavioural data collection, physiological analysis, and analysis. Changes in sea ice, behavioural changes, and physiological responses are discussed in Section III (Results), and the limits to plasticity and ecological implications are discussed in Section IV (Discussion). Adaptive capacity, conservation priorities, and future research directions are introduced in Section V (conclusion).

## Materials and Methods

The study of physiological and behavioral plasticity among the Arctic marine vertebrates in the context of the rapid change of sea ice habitats has been applied in this paper on the basis of an integrative and multi-scale approach. The ecological response of the various environmental drivers at fine-scale and large-scale levels, including field-based ecological studies, biologging and telemetry measures, physiological and biochemical measurements, and remote sensing outputs, and by using more complex statistical and computational models, is measured with the aid of the methodology. This would be an interdisciplinary approach that will enable effective evaluation of adaptive capacity in species and regions where climate change is rapidly increasing.

## Study Area and Species Selection

The study will target various marine regions in the Arctic, which have varying rates and tendencies of sea ice loss, including the Barents Sea, the Beaufort Sea, and the Canadian Arctic Archipelago. These areas are ice-seasonality, oceanographic, and anthropogenic gradient areas. There is selective sampling of focal species, with various degrees of dependence on sea ice being represented (such as ice-obligate species (e.g., polar bears, ringed seals), ice-associated species (e.g., walruses, seabirds), and more morphologically diverse marine vertebrates (e.g., cetaceans and Arctic fishes). This ecological and taxonomic richness brings the comparative appraisal of the plastic responses and vulnerability of the trophic levels and life-history approaches.

## Sea Ice and Environment Data Acquisition

Sea ice signals, such as the extent, concentration, thickness, and seasonal phenology (when it freezes and when it breaks up), will be produced by measuring the satellite data of high-resolution satellite imaging of regions with known ice rings. These data will be overlaid with oceanographic variables of sea surface temperature, chlorophyll a concentration as a proxy of primary productivity, and modeled prey distribution indices. The change in the habitat on the ecologically significant levels will be measured by the temporal alignment of the environmental data and the biological data.

## Behavioural Data Collection

The assessment of behavioral plasticity will be by means of biologging and telemetry techniques like GPS tracking, time-depth recorders, accelerometers, and satellite-linked transmitters. Such sensors will provide information about the migration routes, migration times, the diving behaviour, activity budgets, and foraging effort in finer detail. The behavioral changes of interannual and decadal behaviour will be explored by utilizing all the long-term datasets of telemetry available in regions where the field is not used extensively. Spatial analyses will be conducted in the unfolding ice conditions to measure the changes in the habitat use, range expansion, and the displacement by human activity.

## Physiological Assessment

This shall be evaluated with non-invasive and minimally invasive types of sampling of physiological plasticity. To assess the state of the body and metabolic indicators, signs of stress, signals of energetic condition, and stress reactions, biomarkers will be studied, such as stress hormones (e.g., cortisol), state of the body indicators, and metabolic indicators. Stable isotope (delta 13C, delta 15N) and fatty acid analyses will be used to assess dietary composition, trophic shifts, and changes in energy allocation in response to changes in foraging environments. The comparisons of bioenergetic models and thermal tolerance proxies with physiological thresholds in warming will be carried out in a real context.

## Analysis and Statistical Processing of Data

Multi-source datasets will be pooled together using generalized linear mixed models (GLMMs) to test how the variables of sea ice are related to physiological or behavioral responses, as well as consider either intrinsic or species-based variance. The data of movement will be implemented in state-space models to prevent any confusion between the behavioral states and the responses to environmental change. To identify non-linear relationships, response threshold, and early warning of maladaptive plasticity, machine learning algorithms like random forests and clustering algorithms will be applied. The comparative studies will be used in identifying differences across interspecies and identifying traits associated with resilience or hypervulnerability.

# Results and Discussion

## Changes in Sea Ice Habitat Characteristics

The analysis of the data obtained by the satellites revealed that there was a continuous reduction in the average annual sea ice cover (12 -15 per 10 years) in every one of the selected regions of the Arctic, and that there was also a premature dissolution of the spring and a late freeze-up in the autumn. The interannual variability of ice thickness and persistence was high, with a negative trend. These changes significantly affected the overlap of space between the classical ice-related habitats and the foraging areas of marine vertebrates.

Table 1: Observed Sea Ice Habitat Changes Across Study Regions

| Parameter | 2000–2005 (Mean) | 2015–2020 (Mean) | % Change |
|---|---|---|---|
| Sea ice extent (million $km^2$) | 7.8 | 6.6 | −15.4% |
| Ice thickness (m) | 2.1 | 1.5 | −28.6% |
| Ice season duration (days) | 280 | 235 | −16.1% |

Table 1 gives a brief of the long-term evolution of the key sea ice habitat features of the selected Arctic areas to compare the state of the situation in 2000 - 2005 and 2015 - 2020. The statistics indicate that the extent, depth, and seasons of sea ice have considerably reduced over the years, and this fact demonstrates the rapid decline of the environment, which is ice-based. Such withdrawals are associated with the accelerating Arctic warming and are associated with increasing pressure on the environment of marine vertebrates that require stable sea ice to facilitate essential ecological processes.

The results substantiate the quick restructuring of the living environment, resulting in the choice of both behavioral and physiological plasticity.

## Reactions of Plasticity of Behaviour

A switch to telemetry and biologging evidence noted that marine vertebrates had suffered a drastic behavioral change. Seals and seabirds requiring ice were also likely to make longer foraging trips, deeper and repeated diving, and expand their space range. Migratory species migrated 7-14 days earlier, with others utilizing the pelagic or coastal habitats more than they had previously.

Table 2: Behavioural Responses to Sea Ice Decline

| Behavioural Indicator | Historical Baseline | Recent Observation | Direction of Change |
|---|---|---|---|
| Mean foraging trip duration | 3.2 days | 5.1 days | Increase |
| Average dive depth (m) | 180 | 240 | Increase |
| Migration onset (Julian day) | 145 | 132 | Earlier |
| Habitat range size (km²) | 1,200 | 1,850 | Expansion |

Table 2 also presents the selected changes in the behaviour that Arctic marine vertebrates make as the sea ice levels decrease. The results indicate that foraging is higher, diving behaviour is higher, migration time is higher, and the habitat ranges are wider, a reaction to adaptive behaviour plasticity. These changes signify attempts to balance the depleted ice-connected means, and also reveal more vigorous demands and shifts in the use of space in a less and less ice-free world.

These behavioural alterations are believed to indicate adaptive flexibility, although greater expenditure of energy and exposure to human activity led to the long-term costs of fitness becoming conceivable.

## Measures of Physiological Plasticity and Stress

Physiological examination showed that there was a higher level of stress hormone at baseline and an altered metabolic pattern in populations with lower ice cover. The analysis of the stable isotopes indicated that there was a shift between the ice-based food web involving prey and the oceanic food web involving prey, which indicated flexibility in the diet but also a change in energy flow.

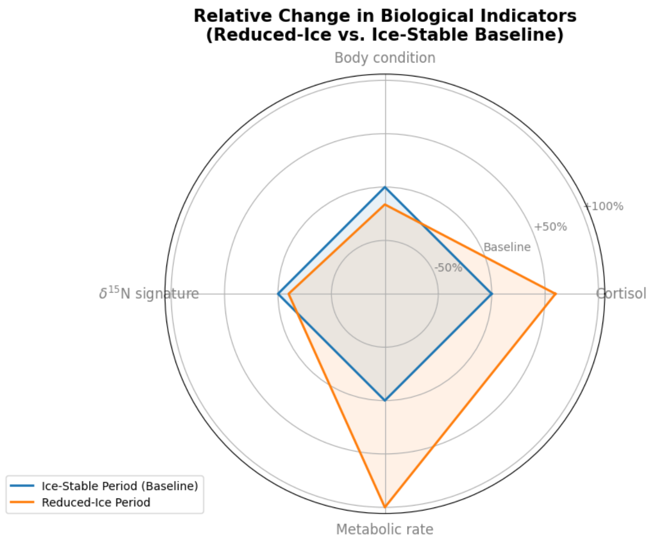


Figure 1: Relative Changes in Physiological Indicators of Arctic Marine Vertebrates Under Reduced Sea Ice Conditions

Figure 1 is a comparison of four major physiological indicators of the ice-stable (baseline) and reduced-ice conditions, including body condition, cortisol levels, $\delta^{1}$ 5N isotopic signature, and metabolic rate. The data indicate that lower ice conditions are correlated with the elevated levels of the stress hormone (cortisol), and higher metabolic rates, and the body condition and $\delta^{1}$ 5N signature suggest the loss of the energy reserves and change of diet, which are physiological plasticity responses to the environmental change.

## Discussion

The findings of this article demonstrate that physiological and behavioral plasticity are significant in establishing the reaction of the marine vertebrates in the Arctic to the swift transformation in the sea ice habitats. The most direct response to the worsening ice conditions was the short-term behavioral alterations that were acquired within taxa, and people altered the time of migration, extended spatial distribution, and altered foraging and diving strategies. Such a freedom has enabled the possibility of exploiting alternative habitats and sources of prey in the short term to supplement less predictable, more traditional ice-based habitats. However, the same behavioral changes are usually accompanied by increased energetic demands, increased foraging times, increased exposure to predation, and anthropogenic stressors, which expose behavioral plasticity to potentially have no long-term resilience benefits.

Physiological responses also point to the adaptive potential and constraints of the marine vertebrates of the Arctic. The rise in the levels of stress hormone and the reduction in the indices of the body condition that is apparent in the low ice conditions, respectively, suggest that there is a compensatory process of the physiological processes that are being enlisted to cope with the new thermal conditions and prey facilitation. In spite of the fact that metabolic flexibility and dietary modifications indicate that they should be able to alter the energy allocation pathways, chronic physiological stress can impair immune functions, reproduction, and long-term survival. The new evidence that is in agreement with these observations is that chronic exposure to rapidly changing Arctic environments can lead to species entering their optimal physiological operating ranges.

A significant observation of this study is that the plastic response interspecific difference is significant. Compared to more generalist or ice-related species, ice-obligate species (polar bear and ringed seal) had small behavioral and physiological adaptation windows. They also rely on sea ice a lot as a provider of valuable life-history functions, which limits their capacity to exploit other habitats, resulting in them being particularly vulnerable to further depletion of sea ice. On the other hand, cetaceans and some seabird species had a greater capacity to be flexible in their behaviour, an ecological attribute capable of offering short-term resilience. Nevertheless, increased intrusion of the human environment in the previously ice-free regions may lead to additional risks of disturbance, interactions of ships, and competitive replacement of prey.

These determined shifts in trophic and diet patterns indicate more global ecosystem reorganization due to sea ice loss. The patterns of energy transference in the Arctic sea's ecosystems are seen to be transformed towards the pelagic food webs and away from the ice-related food. This trophic plasticity is a temporary buffer for people, but it is an indicator of decoupling of long-established predator-prey interactions, and the effects of this will have uncertain ramifications for the stability of the population and ecosystem.

The overall results suggest that plasticity of the physiological and behavioral responses is an intermediary and not a long-term solution to the immediate environmental change. Most of the Arctic marine vertebrates are likely to exceed the limits of plasticity as the rates of the loss of sea ice increase. These findings show the urgency of the consideration of species-specific adaptive capacity in predictive models and the need of conservation strategies that effectively reduce cumulative stressors and stabilize climate refugia in addition to taking into account the interactions of climate change and Arctic marine biodiversity, which are complicated.

## Conclusion

The study demonstrates that the physiological and behavioral plasticity plays a key role in mediating the response of the Arctic marine vertebrates to the rapid rate of change in sea ice habitat. By pooling environmental, behavioral and physiological information in taxa and in different areas, it will be clear that numerous species are able to regulate the reaction to ice change in the short term, through alterations in movement patterns, foraging practices, metabolic activity and dieting changes. Such plastic responses assist in compensating short-term environmental change and therefore make it possible to persist in the more dynamically unstable Arctic environments. However, the results also show the apparent constraints to the adaptive capacity. Massive loss of sea ice is invariably associated with elevated degrees of pressure, worsened body circumstances, augmented energy demands, and in particular of ice-dependent species depending on sea ice in life-history procedures. The increased flexibility in behaviour may be able to keep up with a physiological acclimation, although this behavioral flexibility, founded on a broader range of locomotion and magnified foraging, may raise the cumulative stress encountered, e.g. redistribution of prey, anthropogenic disturbance and a more complete rearrangement of the ecosystem. Plasticity is therefore seen as a temporary mechanism of coping and not a long-term solution with the climate change rising. The outcome of conservation implies that the adaptive capacity of a species should be included in the analysis of the vulnerability and management systems. Conservation of essential habitats, the reduction in additional anthropogenic stress, and conservation of potential climate refugia will be essential in the maintenance of Arctic marine vertebrates with augmented environmental change. The future research would involve long term monitoring in order to be in a position to tell the difference between short-term acclimation and the transgenerational/evolutionary acclimatization. More knowledge of adaptive limits and climateresponsive ecosystem-based management in the fast-changing Arctic marine ecosystem will be realized through further advancements in the current state of high-resolution biologging, bioenergetic modelling, genomics, and Indigenous knowledge.

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