International Journal of Molecular Zoology 2024, Vol.14, No.3, 182-196
http://animalscipublisher.com/index.php/ijmz

Feature Review **Open Access**

Adaptive Strategies of Mammals to Changing Environments: Insights from Behavioral and Physiological Studies

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International Journal of Molecular Zoology, 2024, Vol.14, No.3 doi: 10.5376/ijmz.2024.14.0017
Received: 08 Apr., 2024
Accepted: 19 May, 2024
Published: 10 Jun., 2024

Preferred citation for this article:
Lin X.F., 2024, Adaptive strategies of mammals to changing environments: insights from behavioral and physiological studies, International Journal of Molecular Zoology, 14(3): 182-196 (doi: 10.5376/ijmz.2024.14.0017)

Abstract Mammalian adaptation to changing environments is a critical area of study for understanding survival and evolutionary success. This study aims to explore the behavioral and physiological strategies mammals employ in response to environmental changes, emphasizing the importance of adaptation for species survival. This study establishes a theoretical framework by defining key concepts and reviewing relevant evolutionary theories; through a detailed examination, discusses behavioral adaptations such as migration patterns, social structures, and foraging strategies, alongside physiological adaptations including thermoregulation, water conservation, and reproductive strategies. The genetic basis of these adaptations is analyzed, highlighting the roles of genetic diversity, genomic studies, and epigenetic factors. Case studies of Arctic, desert, and urban mammals illustrate specific adaptive mechanisms. This study also investigates the impacts of climate change on mammalian adaptations, noting shifts in habitat, food availability, and reproductive success. Additionally, human influences such as habitat destruction, pollution, and conservation efforts are considered. This study concludes by identifying future research directions and gaps, emphasizing the need for emerging technologies and interdisciplinary approaches to further understand mammalian adaptation. These insights are crucial for informing conservation strategies and ensuring the resilience of mammalian species in the face of ongoing environmental changes.
Keywords Mammalian adaptation; Behavioral strategies; Physiological mechanisms; Genetic diversity; Climate change impacts

1 Introduction

Mammals exhibit a remarkable ability to adapt to a wide range of environmental conditions, from the frigid Arctic to the arid deserts. These adaptations are crucial for their survival and are driven by both behavioral and physiological changes. For instance, large terrestrial mammals face significant challenges due to climate change, which affects their thermal and water stress levels. They adapt through behavioral modifications such as nocturnal foraging and selecting cooler microclimates, as well as physiological responses like adjusting body temperature regulation (Fuller et al., 2016). Similarly, polar mammals have evolved strategies to cope with extreme cold, food scarcity, and seasonal light variations, including huddling, building shelters, and adjusting their insulation and circulatory systems (Blix, 2016). Urban mammals, on the other hand, demonstrate behavioral changes such as altered home ranges and increased nocturnal activity to adapt to the pressures of urbanization (Ritzel and Gallo, 2020).

Understanding the adaptive strategies of mammals is critical for several reasons. Firstly, it provides insights into how species can survive and thrive in changing environments, which is particularly relevant in the context of rapid climate change. For example, the ability of large mammals to prioritize competing homeostatic systems in response to environmental changes can have significant implications for their fitness and survival (Fuller et al., 2016). Secondly, studying these adaptations can inform conservation efforts, especially in urban areas where human-wildlife conflicts are prevalent. Identifying the traits that enable certain species to adapt to urban environments can help design wildlife-friendly urban spaces (Santini et al., 2018). Additionally, understanding the genetic and physiological mechanisms underlying these adaptations, such as those seen in hypoxia-tolerant mammals, can contribute to broader biological and medical research (Li et al., 2021a; Li et al., 2021b).

This study aims to explore the adaptive strategies of mammals in response to changing environments, focusing on both behavioral and physiological adaptations. By examining a range of species and environmental contexts, from polar regions to urban areas, this study seeks to identify common patterns and unique adaptations that enable mammals to cope with environmental stressors. The scope includes a review of existing literature on mammalian adaptations to climate change, urbanization, and hypoxia, as well as an analysis of the genetic and physiological mechanisms involved. Through this comprehensive approach, this study hope to contribute to a deeper understanding of mammalian resilience and inform future conservation and management strategies.

2 Theoretical Framework

2.1 Definitions and concepts in adaptation and survival

Adaptation in mammals refers to the process by which species undergo changes in their behavior, physiology, and morphology to better survive and reproduce in their changing environments. This can involve genetic changes, phenotypic plasticity, and behavioral modifications (Trubenová et al., 2019). For instance, gene losses have been identified as a significant factor in the adaptive evolution of mammals, contributing to various morphological, physiological, and metabolic adaptations (Sharma et al., 2018). Additionally, behavioral flexibility, such as increased risk-taking and exploration in urban environments, has been observed in non-commensal rodents, indicating a potential adaptive response to human-induced rapid environmental change (HIREC) (Mazza et al., 2020).

2.2 Evolutionary theories relevant to mammalian adaptation

Several evolutionary theories provide a framework for understanding mammalian adaptation. The concept of adaptive plasticity suggests that organisms can develop flexible strategies to cope with environmental stressors, which may be crucial for survival and reproduction under adverse conditions (Ellis and Giudice, 2019). The Price equation, a fundamental theorem in evolutionary biology, helps in understanding how both genetic and non-genetic inheritance contribute to adaptive evolution (Edelaar et al., 2022). Moreover, the idea of distributed adaptation posits that adaptive information can be stored at the population level rather than within individual organisms, highlighting the role of population structure in adaptation (Lamm and Kolodny, 2020).

2.3 Methodologies for studying behavioral and physiological adaptations

To study behavioral and physiological adaptations in mammals, researchers employ a variety of methodologies. Comparative genomics approaches are used to detect gene losses and understand their role in adaptive evolution (Sharma et al., 2018). Meta-analyses of phenotypic trait changes, particularly in response to climate change, help assess whether these changes are adaptive (Radchuk et al., 2019). Experimental evolution, involving controlled environmental conditions and lineage tracking, provides insights into how different environmental complexities influence adaptive processes (Boyer et al., 2021). Additionally, capturing and studying animals from different environments under common conditions allows researchers to distinguish between genetic adaptations and phenotypic plasticity.

3 Behavioral Adaptations to Environmental Changes

3.1 Migration patterns and seasonal behaviors

Migration is a critical adaptive strategy for many mammalian species, allowing them to exploit seasonal resources and avoid unfavorable conditions. For instance, the study on the resilience of migratory behaviors in dynamic environments highlights the role of sociality and cognitive processes such as spatial memory and learning in maintaining and adapting migratory behaviors to changing environmental conditions (Gurarie et al., 2021). Additionally, the movement patterns of large grazing herbivores like the blue wildebeest demonstrate how these animals adjust their migration and foraging behaviors in response to seasonal variations in resource availability and predation risk (Martin et al., 2015). These findings underscore the importance of both social and individual cognitive mechanisms in facilitating adaptive migration strategies.

3.2 Social structure and cooperative behaviors

Social structures and cooperative behaviors are essential for the survival and adaptation of many mammalian species in changing environments (Shukla et al., 2021). Urban mammals, for example, exhibit significant behavioral changes, including increased nocturnal activity and altered social interactions, to cope with the challenges of urbanization (Ritzel and Gallo, 2020). Similarly, the study on non-commensal rodents in urban environments reveals that urban populations exhibit higher behavioral flexibility, which may be crucial for their success in rapidly changing environments (Mazza et al., 2020). These adaptations often involve changes in social behaviors, such as increased vigilance and altered group dynamics, to enhance survival in new and challenging habitats.

3.3 Predation avoidance and foraging strategies

Predation avoidance and foraging strategies are vital for mammalian survival, especially in environments with fluctuating predator pressures and resource availability. The study on the foraging behaviors of aerial predators like the boobies demonstrates the plasticity and flexibility in their foraging strategies, allowing them to adapt to diverse and changing environmental conditions (Gilmour et al., 2018). Additionally, the research on anti-predator behaviors in large herbivores such as impala, wildebeest, and zebra shows that these animals employ a range of strategies, including flight, vigilance, and alarm-calling, which are modulated based on predator characteristics and perceived risk levels (Figure 1) (Palmer and Packer, 2021). These adaptive behaviors are crucial for minimizing predation risk while optimizing foraging efficiency.

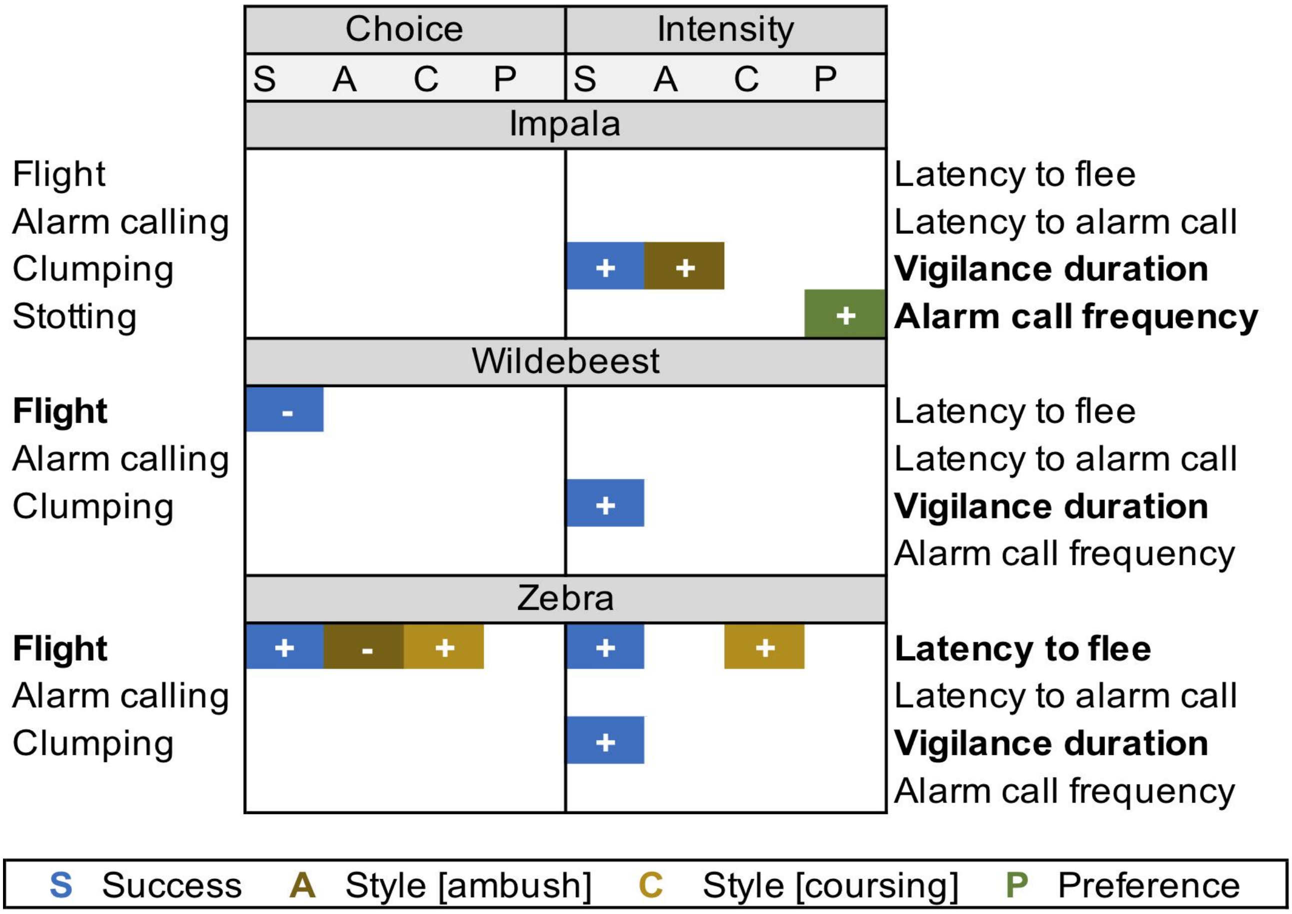

Figure 1 Anti-predator behavioral strategies adopted by focal prey species relative to predator traits (Adopted from Palmer and Packer, 2021)

Image caption: Impala relied on the same suite of behaviors, modulating the intensity of their response relative to multiple predator traits. Wildebeest altered the type and intensity of response, but only responded to predator capture success. Zebra adjusted both the type and intensity of behaviors performed in response to multiple characterizations of threat. Colored blocks correspond to predator traits that were strongly supported to affect response performance with +/- indicating the direction of the response. Relative predator density was never a significant driver of anti-predator tactics and is therefore unlisted (Adopted from Palmer and Packer, 2021)

The research of Palmer et al. (2021) compares the anti-predator behaviors of impalas, wildebeests, and zebras in response to various predator traits. Impalas consistently use the same set of behaviors, adjusting their intensity based on predator attributes, such as vigilance duration and alarm call frequency. Wildebeests change both the type and intensity of their responses but only in relation to the predator's capture success. Zebras show the most varied strategies, modifying both the type and intensity of their behaviors in response to multiple predator traits, including flight and clumping behaviors. This comparison highlights that different species adopt distinct strategies to cope with predation risks, reflecting their unique ecological adaptations. Impalas rely on a flexible but consistent approach, wildebeests are more selective, responding significantly to direct threats, while zebras use a broad range of tactics to mitigate various predation risks. Understanding these behaviors can provide insights into species-specific adaptations and predator-prey dynamics in their natural habitats.

In summary, mammals exhibit a wide range of behavioral adaptations to cope with changing environments, including migration and seasonal behaviors, social structure adjustments, and sophisticated predation avoidance and foraging strategies. These adaptations are essential for their survival and highlight the complex interplay between environmental pressures and behavioral responses.

4 Physiological Adaptations to Environmental Changes

4.1 Thermoregulation mechanisms

Mammals have developed a variety of thermoregulation mechanisms to adapt to changing environmental temperatures. For instance, marine mammals have evolved unique genomic adaptations to manage heat loss in aquatic environments. Genes associated with the formation of blubber (*NFIA*), vascular development (*Sema3E*), and heat production by brown adipose tissue (*UCP1*) play crucial roles in these adaptations (Figure 2) (Yuan et al., 2021). Additionally, polar mammals utilize behavioral and physiological strategies such as huddling, building shelters, and seasonal changes in insulation through fur, plumage, and blubber to maintain core body temperature (Blix, 2016). The hypothalamic neuromodulation of thermoregulation is another critical area, where neural pathways and anatomical structures regulate body heat autonomously and behaviorally (Mota-Rojas et al., 2021). Furthermore, skeletal muscle plasticity contributes significantly to thermogenesis, with mechanisms like shivering and non-shivering thermogenesis enhancing metabolic heat production (Wright and Sheffield-Moore, 2021).

The research of Yuan et al. (2021) provides a comprehensive overview of the convergent evolution of thermoregulation in marine mammals, emphasizing the roles of genetic and cellular mechanisms. Panel A illustrates how *NFIA* regulates the differentiation of mesenchymal precursors into white or brown adipocytes, with brown adipocytes playing a crucial role in thermogenesis through the activity of *UCP1*. This thermogenic process helps maintain body temperature, supported by the well-developed retia mirabilia in marine mammals, which facilitates efficient heat transfer. Panel B highlights a unique amino acid change in the *NFIA* gene common to marine mammals, suggesting an evolutionary adaptation for thermoregulation. Similarly, panel C shows a conserved amino acid change in the *Sema3E* gene among cetaceans and pinnipeds, indicating another adaptation for maintaining thermal balance in aquatic environments. Panel D demonstrates the conservation of the *UCP1* gene across species, with significant sequence conservation shown in the VISTA plot, highlighting its essential role in brown adipocyte function and thermoregulation. This genetic and physiological convergence underscores the adaptive strategies marine mammals have evolved to thrive in cold aquatic habitats.

4.2 Water conservation and metabolic adaptations

Water conservation is vital for mammals living in arid environments. For example, the Karoo scrub-robin exhibits physiological adaptations that include variations in metabolic rates and gut microbiome composition, which are associated with environmental features and genetic variations underlying energy metabolic pathways (Ribeiro et al., 2019). Hibernation is another strategy that allows mammals to survive periods of water and food scarcity. During hibernation, metabolic, neuronal, and hormonal cues regulate the reduction of body temperature and metabolic rate, conserving water and energy (Mohr et al., 2020). Additionally, the study of gene losses in mammals has revealed that certain gene deletions may contribute to metabolic adaptations, facilitating survival in specific environments (Sharma et al., 2018).

4.3 Reproductive adaptations and strategies

Reproductive adaptations are essential for the survival of mammalian species in changing environments. Polar animals, for instance, exhibit profound tolerance to hypothermia in newborns, with altricial animals depending on parental care for warmth and precocial mammals utilizing non-shivering thermogenesis in brown adipose tissue

(Blix, 2016). In arid environments, reproductive strategies may involve adjustments in metabolic phenotypes to ensure energy homeostasis and successful reproduction despite harsh conditions (Ribeiro et al., 2019). Furthermore, the endocrine regulation of development and metabolism in response to environmental cues plays a significant role in reproductive adaptations, as seen in the hormonal control mechanisms in Drosophila, which are comparable to those in mammals (Koyama et al., 2020).

By understanding these physiological adaptations, we can gain insights into how mammals have evolved to thrive in diverse and changing environments, ensuring their survival and reproductive success.

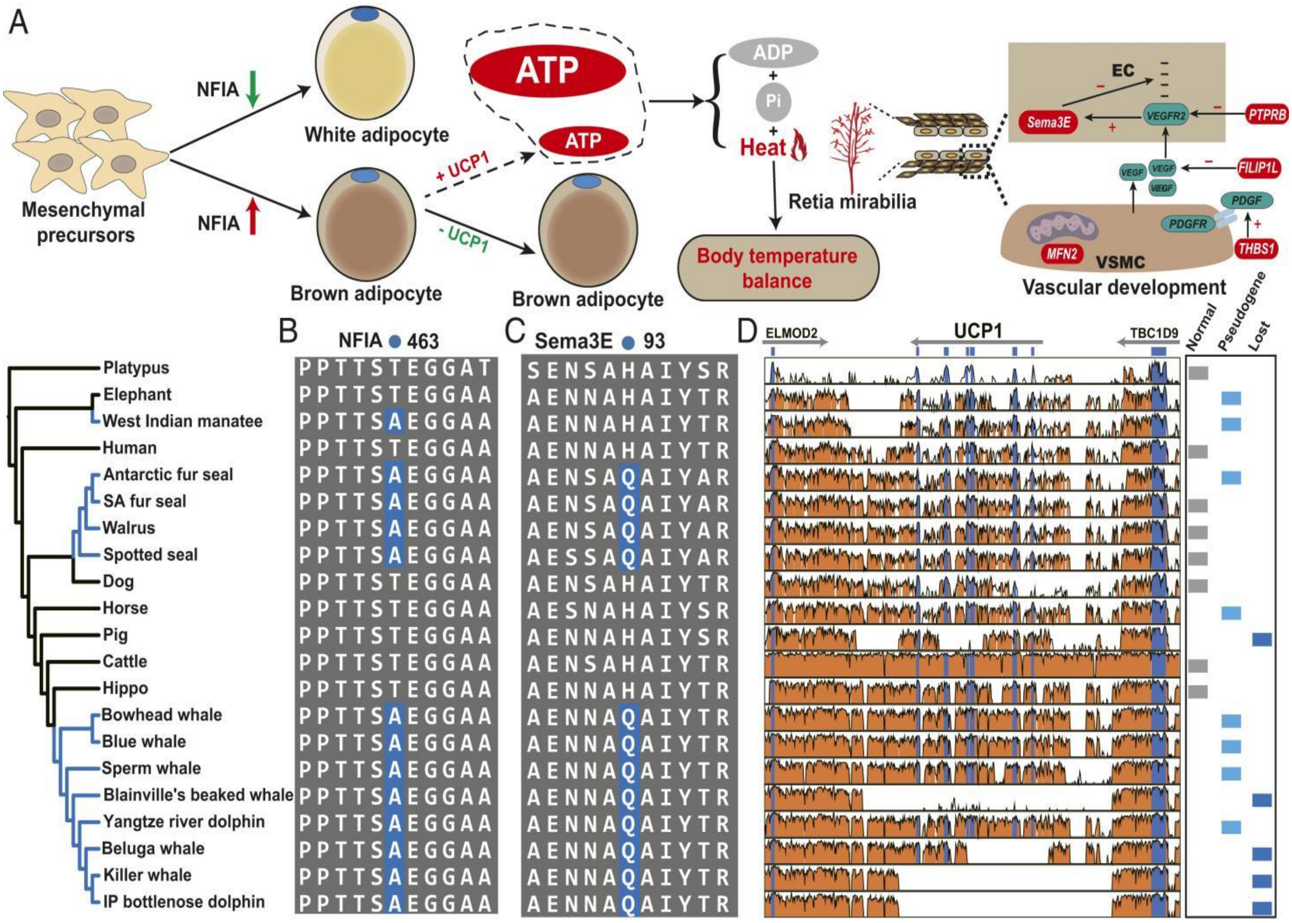

Figure 2 Convergent evolution of thermoregulation in marine mammals (Adopted from Yuan et al., 2021)

Image caption: (A) Schematic diagram of thermoregulation in marine mammals. Up-or down-regulation of nuclear factor I A (*NFIA*) affects the cell fate of mesenchymal precursors, the integrity of *UCP1* gene affects the fate of brown adipocyte, and the well-developed retia mirabilia in marine mammal aids in the heat transfer to maintain body temperature balance. VSMC, vascular smooth muscle cell; EC, endothelial cell. (B) A unique amino acid change in the *NFIA* gene of marine mammals. Shared amino acid change are highlighted in blue, IP, Indo-Pacific. (C) A unique amino acid change in the *Sema3E* gene of cetaceans and pinnipeds. Blue highlighting indicates the shared amino acid change. (D) VISTA sequence conservation plot of the *UCP1* gene, using goat (ARS1) as a reference (Adopted from Yuan et al., 2021)

5 Genetic Basis of Adaptation

5.1 Role of genetic diversity in adaptive potential

Genetic diversity plays a crucial role in the adaptive potential of species. It provides the raw material for natural selection to act upon, enabling populations to adapt to changing environments. For instance, research on fish population genomics has shown that adaptive evolution often involves shifts in allele frequencies rather than the fixation of beneficial alleles, highlighting the importance of standing genetic variation in maintaining evolutionary potential (Bernatchez, 2016). Similarly, studies on songbirds have demonstrated that preexisting genetic variants are the predominant source of adaptation, underscoring the significance of genetic diversity in evolutionary processes (Lai et al., 2019).

5.2 Genomic studies and findings in adaptive traits

Advances in genomic methods have facilitated the identification of loci, genes, and mutations underlying adaptive traits. For example, genomic analyses have revealed that gene losses can contribute to morphological, physiological, and metabolic adaptations in mammals, suggesting that gene loss is a widespread mechanism for adaptation (Sharma et al., 2018). Additionally, research on the genetic architecture of adaptation has shown that adaptive loci can be identified by examining genomic regions under selection and connecting these variants to phenotypic traits (Bomblies and Peichel, 2022). These findings provide valuable insights into the molecular mechanisms driving adaptation and highlight the complexity of the genetic basis of adaptive traits.

5.3 Epigenetic factors influencing adaptation

Epigenetic mechanisms, such as DNA methylation, histone modifications, and non-coding RNAs, play a significant role in environmental adaptation. Epigenetic variation can contribute to phenotypic plasticity, allowing organisms to rapidly adapt to new environments without genetic changes. For instance, studies on invasive species have shown that epigenetic responses can facilitate rapid adaptation, even in populations with minimal genetic diversity (Carneiro and Lyko, 2020). Moreover, research on clonal animals and plants has demonstrated that epigenetic mechanisms support phenotypic plasticity and stable adaptation to different environments (Vogt, 2017; Vogt, 2022). The interplay between genetic and epigenetic variation is crucial for understanding the adaptive capacity of populations, as both types of variation can jointly promote rapid adaptation to changing environments (Stajic and Jansen, 2021; Chen et al., 2022).

In summary, the genetic basis of adaptation involves a complex interplay between genetic diversity, genomic changes, and epigenetic mechanisms. Understanding these factors is essential for predicting the adaptive potential of species and developing effective conservation and management strategies.

6 Case Studies in Place

6.1 Arctic mammals: adaptations to extreme cold

Arctic mammals have developed a range of adaptations to survive the extreme cold and seasonal variations in their environment. These adaptations include behavioral, physical, and physiological strategies (Davidson et al., 2020). For instance, many Arctic mammals engage in behaviors such as huddling and shelter building to reduce exposure to the cold. Physiologically, they exhibit seasonal changes in insulation through fur, plumage, and blubber, and circulatory adjustments to preserve core temperature by cooling the periphery and extremities. Additionally, newborn altricial animals show profound tolerance to hypothermia but rely on parental care for warmth, while precocial mammals are well insulated and use non-shivering thermogenesis in brown adipose tissue to generate heat (Blix, 2016). Behavioral plasticity also plays a crucial role, as seen in wild reindeer in high-Arctic Svalbard, which adjust their space use in response to extreme weather events like rain-on-snow and icing, thereby reducing body mass loss and mortality rates, and increasing fecundity (Loe et al., 2016).

6.2 Desert mammals: strategies for surviving in arid environments

Desert mammals face the challenges of water and food scarcity, as well as extreme temperatures. Recent genomic research has highlighted the genetic mechanisms underlying these adaptations, revealing a large overlap in functional classes of genes and pathways among different desert mammals. These genetic adaptations are crucial for managing water retention, thermoregulation, and efficient nutrient utilization. However, the complexity of these adaptations and the variety of phenotypes involved necessitate further studies to develop accurate genotype-phenotype-environment maps (Figure 3) (Rocha et al., 2021). The genetic basis of these adaptations underscores the importance of understanding the evolutionary processes that enable mammals to thrive in such harsh environments.

The research of Rocha et al. (2021) provides a detailed overview of the genomic strategies used to identify genes associated with desert adaptation in various species. Panel A focuses on population-specific adaptations, highlighting genetic diversity and long haplotypes specific to desert and non-desert populations. Panel B delves into species-specific adaptations, utilizing metrics like dN/dS ratios and gene family evolution to compare desert-adapted species with their non-desert counterparts. Panel C examines differential gene expression in wild-caught and laboratory conditions, showing how gene expression varies between species and populations based on environmental factors such as water availability. Panel D integrates these findings into functional categories and pathways, linking genes involved in energy and fat metabolism, cardiac output, oxidative stress, glucose transport, and water retention to specific adaptive phenotypes. These phenotypes include reduced energy expenditures, enhanced use of metabolic water, increased sodium excretion, and increased water reabsorption, all crucial for survival in arid environments. This comprehensive approach underscores the complex genetic and physiological mechanisms underlying desert adaptation.

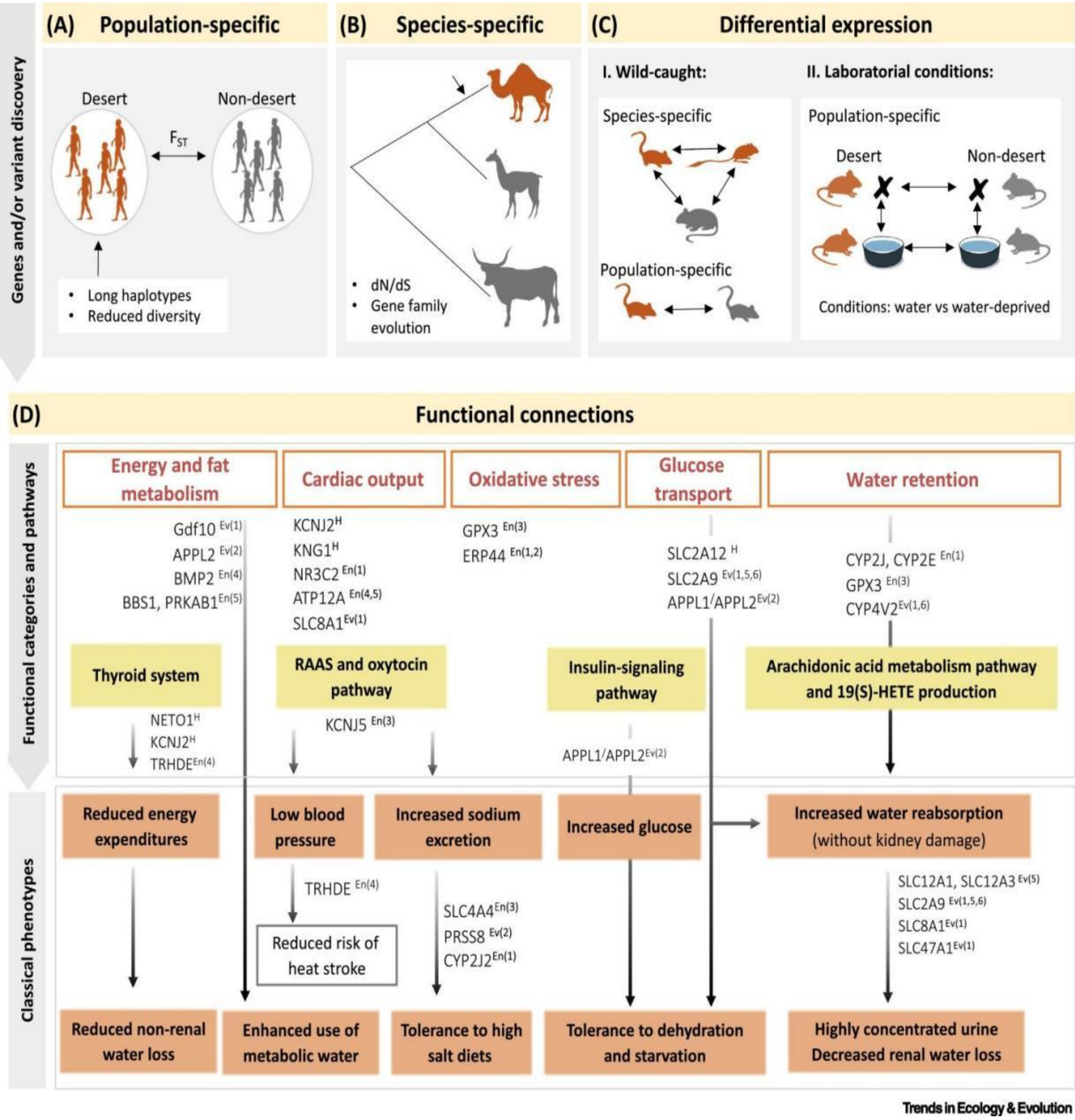

Figure 3 Genomic approaches used to identify genes underlying desert adaptation (Adopted from Rocha et al., 2021)

6.3 Urban mammals: behavioral changes in response to human activity

Urbanization imposes new environmental pressures on wildlife, leading to significant behavioral changes in urban mammals. A systematic review of urban mammal behavior found that omnivores and carnivores are the most studied groups, with common behavioral changes including alterations in home range, diet preference, activity budget, vigilance, flight initiation distance, and increased nocturnal activity (Ritzel and Gallo, 2020). These changes are driven by the need to adapt to the urban environment, which often involves increased human presence and altered resource availability. Additionally, urban mammals tend to produce larger litters, and traits such as body size, behavioral plasticity, and diet diversity play varying roles in their adaptation to urban settings (Santini et al., 2018). Studies on non-commensal rodents, such as the common vole, have shown that urban populations exhibit higher risk-taking and exploratory behaviors compared to their rural counterparts, which may be due to behavioral flexibility rather than genetic differences (Depasquale et al., 2020; Mazza et al., 2020). This behavioral plasticity is crucial for coping with the rapid environmental changes induced by urbanization.

By examining these case studies, we gain a deeper understanding of the diverse adaptive strategies employed by mammals to survive and thrive in varying environments, from the extreme cold of the Arctic to the arid deserts and bustling urban landscapes.

7 Impacts of Climate Change on Mammalian Adaptations

7.1 Shifts in habitat and distribution

Climate change is driving significant shifts in the habitat and distribution of mammalian species. As temperatures rise and precipitation patterns change, many species are moving to new areas to find suitable environmental conditions. For instance, species are migrating poleward or to higher elevations to escape the heat (Pecl et al., 2017). This redistribution can lead to novel ecosystems and altered ecological communities, which may disrupt existing species interactions and create new ones. Additionally, the realized climatic niche of many terrestrial mammals is shrinking due to climate change and human activities, with over half of the studied species experiencing a reduction in their niche (Moreno et al., 2020; Marco et al., 2021). Marine mammals are also affected (Chikina et al., 2016), with high-latitude species experiencing some of the most significant habitat changes due to melting ice and changing sea temperatures (Silber et al., 2017).

7.2 Alterations in food availability and diet

Climate change is altering the availability and distribution of food resources, which in turn affects the diet of mammalian species. For example, the endangered brown bear population in the Cantabrian Mountains is expected to face a decline in the availability of key plant species that serve as their main food sources due to climate warming (Penteriani et al., 2019). This reduction in food availability may force bears to shift towards a more carnivorous diet, increasing conflicts with livestock farmers and affecting their fat storage before hibernation. Similarly, unpredictable food supply due to climate change can influence the endocrine and metabolic functions of terrestrial mammals, impacting their survival and persistence (Fuller et al., 2020).

7.3 Changes in reproductive timing and success

Climate change is also affecting the reproductive timing and success of mammalian species. Many species rely on photoperiod cues to time their reproduction with optimal food availability. However, climate change is causing mismatches between these cues and actual environmental conditions, leading to suboptimal breeding times (Walker et al., 2019). For instance, African wild dogs have shown a climate-induced phenological shift that is contributing to lower reproductive success, highlighting the complexity of species' responses to climate change (Abrahms et al., 2022). Additionally, the potential for genetic adaptation to climate change may provide some buffer against these impacts, but it is not guaranteed to prevent declines in reproductive success across all taxa (Meester et al., 2018; (Razgour et al., 2019).

In summary, climate change is driving significant shifts in habitat and distribution, altering food availability and diet, and affecting reproductive timing and success in mammalian species. These changes underscore the need for dynamic conservation strategies that consider the multifaceted impacts of climate change on mammalian adaptations.

8 Human Influence on Mammalian Adaptation

8.1 Habitat destruction and fragmentation

Human activities have led to significant habitat loss and fragmentation, which have profound effects on mammalian populations (Gaynor et al., 2018). A meta-analysis revealed that habitat fragmentation decreases genetic diversity in mammals, with larger-bodied species and forest-dependent species being the most negatively affected (Lino et al., 2019). Additionally, primates, which often have slow life histories, face severe challenges due to habitat loss, making gene-based adaptations unlikely to evolve quickly enough to counteract these changes (Kalbitzer and Chapman, 2018). The disruption of animal movement due to human disturbance further exacerbates these issues, leading to negative impacts on fitness, survival, and population viability (Doherty et al., 2021).

8.2 Pollution and its effects on physiology and behavior

Pollution has significant physiological and behavioral impacts on mammals. For instance, adaptive introgression has enabled some species, like the Gulf killifish, to rapidly evolve resistance to extreme environmental pollution through the introduction of advantageous genetic variability from non-native species (Oziolor et al., 2019). Moreover, forest degradation has been shown to alter stress hormone levels and immune responses in mammals, indicating that pollution and habitat degradation can mediate the adaptiveness of species to changing environments (Messina et al., 2018). Neurobiological studies also suggest that rapid environmental changes due to pollution can outpace the adaptive responses of nervous systems, highlighting the need for further research into the cellular and molecular mechanisms underlying these adaptations (Michaiel and Bernard, 2022).

8.3 Conservation efforts and their impact on adaptive strategies

Conservation efforts play a crucial role in mitigating the negative effects of human activities on mammalian adaptation. Understanding the behavioral flexibility of primates, for example, can help optimize conservation strategies by constructing informed management plans that consider species-specific responses to environmental changes (Teitelbaum et al., 2021). Additionally, identifying traits that favor urban adaptation in mammals, such as larger litter sizes and behavioral plasticity, can inform the design of wildlife-friendly urban environments and help mitigate human-wildlife conflicts (Santini et al., 2018). Long-term studies on wildlife behavior in urban settings are essential to promote successful urban wildlife management and conservation (Ritzel and Gallo, 2020).

By addressing habitat destruction, pollution, and implementing effective conservation strategies, we can better support the adaptive capacities of mammals in the face of rapidly changing environments.

9 Future Directions and Research Gaps

9.1 Emerging technologies in studying mammalian adaptation

The study of mammalian adaptation to changing environments has greatly benefited from advancements in technology. For instance, the use of isotopes in free-living mammals has enabled detailed studies of water turnover and diet in the field, while thermal imaging and radiotelemetry have facilitated the study of heat loss, body temperature, and animal movements in their natural habitats (Ball et al., 2017). Additionally, genomic approaches have revealed the importance of gene losses in adaptive evolution, shedding light on the molecular and cellular mechanisms underlying phenotypic adaptations in mammals (Snyder-Mackler and Lea, 2018). These technologies not only enhance our understanding of current adaptive strategies but also provide tools for predicting future responses to environmental changes.

9.2 Interdisciplinary approaches to understanding adaptation

Understanding mammalian adaptation requires an interdisciplinary approach that integrates behavioral, ecological, physiological, and genetic perspectives (Bush et al., 2016). Long-term field studies have been instrumental in revealing how mammals adapt to their natural environments and respond to rapid global changes. Moreover, studies on urban mammals have highlighted the importance of behavioral plasticity and ecological traits in adaptation to novel environments (Santini et al., 2018). The integration of individual-based modeling (IBM) with eco-evolutionary dynamics has also provided insights into the adaptive responses of species to environmental changes, emphasizing the need for models that consider genetic adaptation, phenotypic plasticity, and dispersal simultaneously (Romero-Mujalli et al., 2018). Such interdisciplinary approaches are crucial for developing comprehensive strategies for wildlife conservation and management.

9.3 Identified gaps and suggestions for future research

Despite significant progress, several gaps remain in our understanding of mammalian adaptation. One major gap is the limited research on ecophysiology within long-term studies, which is essential for understanding how mammals respond to rapid global changes (Schradin and Hayes, 2017). Future research should focus on integrating physiological data with long-term ecological and behavioral studies to provide a more holistic view of adaptation. Additionally, while individual-based models have advanced our understanding of genetic adaptation, there is a lack of models that simultaneously address genetic adaptation, phenotypic plasticity, and dispersal. Future models should incorporate these adaptive responses as evolving traits with their associated costs and benefits. Furthermore, the role of gene loss in adaptive evolution is an emerging area that warrants further investigation, as it has the potential to reveal novel insights into the genomic basis of adaptation (Sharma et al., 2018). Finally, there is a need for more long-term studies on wildlife behavior in urban environments to better understand the adaptive strategies of urban mammals and inform urban wildlife management (Ritzel and Gallo, 2020). Addressing these gaps will enhance our ability to predict and mitigate the impacts of environmental changes on mammalian species.

10 Concluding Remarks

Mammals exhibit a wide range of adaptive strategies to cope with changing environments, which can be broadly categorized into behavioral, physiological, and genetic adaptations. Behavioral adaptations include changes in activity patterns, such as nocturnal foraging to avoid heat stress, and increased risk-taking and exploration in urban environments. Physiological adaptations encompass mechanisms like hibernation, which allows mammals to survive periods of resource scarcity by reducing metabolic rates, and the development of hypoxia tolerance in species like the naked mole-rat. Genetic adaptations, including gene losses, have also been identified as significant contributors to phenotypic changes that enhance survival in specific environments.

Understanding these adaptive strategies is crucial for conservation and management efforts, particularly in the context of rapid environmental changes due to urbanization and climate change. For instance, recognizing the traits that enable certain mammals to thrive in urban settings can inform the design of wildlife-friendly urban environments and help mitigate human-wildlife conflicts. Additionally, insights into the physiological and genetic mechanisms underlying adaptation can guide conservation strategies aimed at enhancing the resilience of vulnerable species. For example, long-term monitoring of large mammals' responses to climate change can help predict their future distribution and survival, thereby informing habitat protection and restoration efforts.

The study of adaptive strategies in mammals provides valuable insights into the complex interplay between behavior, physiology, and genetics in response to environmental challenges. Future research should focus on integrating these different levels of adaptation to develop a more comprehensive understanding of how mammals cope with changing environments. This includes exploring the role of epigenetic mechanisms and transgenerational effects in adaptation, as well as investigating the potential for adaptive responses in other taxa, such as ectotherms and microbes. Ultimately, a deeper understanding of these adaptive strategies will enhance our ability to predict and mitigate the impacts of environmental change on biodiversity.

Acknowledgements

Thank you to every anonymous reviewer for their hard work and feedback.

Conflict of Interest Disclosure

Author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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