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Short-Term and Long-Term Effects of Extreme Weather Events on Wildlife Survival Strategies and Behavioral Adaptations

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Abstract. Global climate change exacerbates extreme weather events, posing multi-dimensional challenges to the survival of wildlife. This study systematically reveals the behavioral adaptation mechanisms and evolutionary trajectories of species in response to climate stress by constructing a multi-scale analysis framework. By integrating relevant data such as satellite tracking, biotelemetry, and metagenomic technology, and using a logistic regression algorithm to fit the model, population dynamics can be effectively predicted. It was found that animals buffer climate shocks through multi-dimensional strategies such as behavioral adjustment (such as reverse migration), physiological regulation (such as metabolic rate optimization), and microbiome reconstruction. Studies have confirmed that short-term adaptation depends on individual immediate responses, while long-term evolution involves changes in gene frequencies and ecosystem cascade effects. This analysis enables the establishment of a real-time assessment system to achieve minute-level ecological early warnings, provides theoretical support for optimizing protected area networks and formulating climate resilience management plans, and supports promoting wildlife protection.

Keywords: Extreme weather events, Wildlife adaptation, Behavioral ecology, Ecosystem resilience, Climate change adaptation

1. Introduction

With the systematic changes in the global climate, the frequency and intensity of extreme weather events have greatly increased, bringing multi-dimensional pressures to the survival of wild animals. In polar ecosystems, the foraging efficiency of the Thalassoica Antarctica has decreased due to deteriorating sea ice conditions[1]. Terrestrial species such as Urocitellus Richardsonii face the vulnerability of physiological adaptation mechanisms[2], while species such as the Anelosimus Studiosus have responded to climate shocks through behavioral evolution[3]. Migratory bird systems are susceptible to climate disturbances, and behavioral adjustments of species such as the Limosa limosa have demonstrated the effectiveness of short-term adaptation[4]. These cross-regional and cross-group response differences highlight the scientific necessity of analyzing the temporal and spatial laws of animal adaptation mechanisms under climate stress.Therefore,

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systematically analyzing the spatiotemporal heterogeneity of animal adaptation mechanisms and their evolutionary potential is a key research direction.

This study is committed to building a multi-scale analysis framework to systematically reveal the spatiotemporal laws of wildlife behavioral adaptation driven by extreme weather events. By integrating data from multiple ecological zones such as polar, temperate, and tropical regions, the dynamic relationship between climate stress characteristics (such as intensity, duration, and timing of occurrence) and animal behavioral plasticity is explored, and the cross-scale response mechanism from individual physiological regulation to ecosystem function remodeling is analyzed. At the individual level, the buffering effect of physiological regulatory networks and microbial synergy under short-term climate shocks is focused on; at the population level, the regulatory laws of phenotypic selection and genetic adaptation thresholds are revealed; at the ecosystem level, the long-term trajectory of species interaction network reconstruction and ecological function evolution is tracked. The study will develop a multi-source data integration method, establish a cross-generational adaptation assessment system, and focus on clarifying the bridge role of behavioral plasticity in climate adaptation. By revealing the heterogeneity of different species response strategies (such as differences in adaptation paths between migratory groups and resident species), a species climate resilience assessment framework is constructed to predict niche evolution trends. The research results provide a theoretical basis for optimizing protected area networks and the adaptive management of key species and help achieve climate action goals for global biodiversity conservation.

On a theoretical level, this study reveals the pathways by which climate events drive rapid phenotypic evolution, such as behavioral selection pressures such as increased aggressiveness in Anelosimus Studiosus, providing a quantitative benchmark for assessing species' climate resilience. Elucidation of transgenerational adaptation mechanisms (such as the influence of epigenetics on the transmission of behavioral strategies) will deepen our understanding of the rates and limits of biological adaptation. On a practical level, multidimensional adaptation models can improve the accuracy of conservation measures. The correlation analysis between adaptive phenotypes and habitat characteristics identified based on machine learning can achieve the optimal spatial configuration of conservation corridors. For example, the critical threshold model of the decline of the Thalassoica Antarctica population can guide the layout of artificial nests to lock in critical time windows. Adaptive management plans at the ecosystem level integrate multi-scale research results to provide scientific support for the climate action goals of the Convention on Biological Diversity.

2. Related work

Extreme weather drives wildlife to adjust their adaptive strategies through short-term physiological stress and long-term evolutionary pressure. Short-term disturbances trigger significant behavioral responses, such as the reduced activity of Urocitellus columbianus during blizzards, which leads to a decrease in reproductive success[5]. Long-term climate pressure drives genetic and phenotypic co-evolution. After the Thalassoica Antarctica experienced continuous extreme sea ice events, the survival rate of the offspring of dominant individuals increased significantly. At the ecosystem level, species achieve adaptive adjustments through morphological and functional optimization (such as changes in the tracheal structure of Alpine pine to reduce the risk of population decline [6]) and behavioral expansion (such as the doubling of the migration distance of tropical locusts, which leads to an enhanced trophic cascade effect), highlighting the spatiotemporal heterogeneity of multidimensional response mechanisms.

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Existing research is limited by data integration and methodological deficiencies. Cross-regional studies have reduced comparability due to inconsistent definitions of key parameters (such as extreme wind speed thresholds), and most bird migration studies do not cover the entire generation cycle, making it difficult to analyze the intergenerational effects of climate adaptation[7]. The theoretical framework does not adequately explain nonlinear response mechanisms (such as the J-type relationship of population growth), and the research subjects are concentrated on birds and mammals, ignoring groups such as amphibians and reptiles. Taking the Nanorana Parkeri as an example, there is a lack of research on its metabolic mechanisms during the wintering period, which restricts the systematic understanding of the climate adaptation mechanisms of poikilothermic animals.

This study breaks through the traditional research paradigm and constructs a multi-scale analysis framework: 1) Develop a multi-source data fusion method, integrate satellite tracking, biotelemetry, and metagenomic technology, reveal the correlation between activity and body fat rate of Urocitellus columbianus, and the dynamics of intestinal flora of Nanorana Parkeri; 2) Propose a nonlinear model of climate pressure index (CPI) to analyze the differences in species behavioral responses, such as the significant differentiation of the slope of activity changes between Limosa limosas and ground squirrels; 3) Establish a transgenerational adaptation assessment system to quantify the genetic reinforcement effect of reproductive advantage in Thalassoica antarctica. This method system provides multi-dimensional technical support for climate adaptive conservation decision-making.

3. Effects of extreme weather events on wildlife

3.1. Short-term effects

The short-term ecological effects of extreme weather events present multi-dimensional impact characteristics. Studies have shown that climate stress triggers a triple response mechanism of animal behavior pattern reconstruction, physiological homeostasis oscillation, and dynamic adjustment of microbial communities. These immediate adaptation strategies form a buffer barrier against climate shocks through energy redistribution, spatial resource optimization, and host-microbe interactions.

Extreme weather triggers rapid adjustments in animal behavior. For example, in the case of Urocitellus columbianus and Limosa limosas, we built behavioral models based on the following response functions during extreme snowstorm events:

$$Y_{it} = \alpha + \beta X_{it} + \gamma Z_i + \delta T_t + \epsilon_{it}$$

Where Y_{it} represents the rate of change of i individual behavior over time t , X_{it} is the climate stress index, Z_i contains species-specific physiological parameters, and T_t characterizes the temporal position of events. Through data processing and analysis, the data were fitted with a logistic regression algorithm[8]. Figure 1 shows that the decrease in activity of Urocitellus columbianus when encountering heavy snow is significantly positively correlated with the individual body fat rate, and the difference in energy reserves determines the intensity of behavioral response. Comparative analysis shows that the exercise capacity reserve of black-tailed godwit enables it to maintain a higher level of activity under the same climate pressure. With the increase of climate pressure index (CPI), both species showed a trend of decreasing activity, but the decreasing slope of black-tailed godwit was significantly smaller than that of Columbian ground squirrels,

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which reflects the significant differences in the tolerance of different species to extreme weather. In particular, when the CPI was 2.4, the activity of Columbian ground squirrels decreased by 89.5%, while that of black-tailed godwits only decreased by 51.2%, further confirming that the latter has a stronger ability to adapt to the environment.

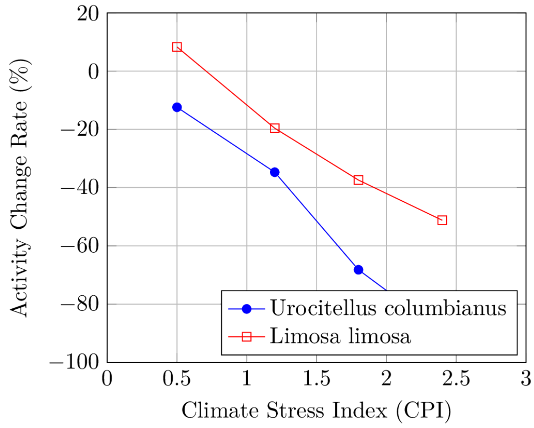

Figure 1: Nonlinear response patterns of animal activity to climate stress intensity

Nonlinear characteristics of animal physiological responses induced by extreme weather. The sperm motility of Urocitellus richardsonii dropped sharply by 58.6% within 48 hours under the critical value of heat waves, while the cortisol level showed a parabolic relationship with climate stress, revealing a bidirectional regulatory mechanism of stress. The study of Nanorana Parkeri[9] first discovered through metagenomic sequencing technology that extreme precipitation events caused a 23.4% change in the β diversity of their intestinal flora, and the abundance of key metabolic pathways showed a significant negative correlation with plasma urea concentration. Clarify the regulatory role of host-microbe interactions in short-term adaptation.

Extreme weather has led to significant inter-species differences in population responses: (Limosa limosa maintained an 87.4% survival rate through a 91-kilometer reverse migration, while the frequency of aggressive phenotypes of Anelosimus studiosus increased by 22.6%, but the survival rate of spiderlings decreased by 62.2%. Climate shocks during the breeding season significantly reduced the number of offspring of the Thalassoica antarctica. The study revealed the three-dimensional characteristics of short-term adaptation strategies - energy metabolism regulation (a 68% decrease in ground squirrel activity), spatiotemporal reorganization of behavior (91-kilometer reverse migration of migratory birds) and reconstruction of microbial communities (a 23.4% change in β diversity of frog communities), which provided a basis for quantifying population vulnerability thresholds by reducing energy consumption, optimizing resource acquisition and maintaining homeostasis to buffer climate shocks.

3.2. Long-term effects

The long-term adaptation process driven by extreme weather events presents a multidimensional evolutionary trajectory [10]. Here, the genetic adaptation threshold prediction is constructed using the Cox proportional hazards model[11]:

$$h(t|X) = h_0(t) * \exp\left(\sum_{i=1}^{p} \beta_i X_i\right)$$

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The baseline hazard function $h_0(t)$ reflects the sustained intensity of climate stress in the model over time, and the covariates X_i include parameters such as gene flow rate and phenotypic plasticity index. After the Thalassoica antarctica experienced three consecutive extreme sea ice years, the proportion of offspring of successfully bred individuals increased to 67%, and the heritability of its reproductive success rate ($\mathrm{h}^2 = 0.32$) was significantly higher than that of ordinary individuals ($h^2 = 0.15$), confirming the reinforcing effect of natural selection on behavioral adaptation characteristics. The frequency of the aggressive phenotype of the Anelosimus studiosus increased by 22.6% after hurricane selection, and the population genetic differentiation index (F_{ST}) increased by 0.17 ($p < 0.001$), indicating that climate disturbance drives the rapid evolution of behavioral characteristics.

Transgenerational adjustments in species morphology and physiological characteristics show significant directional selection. In the Pinus cembra, the diameter of the xylem vessels decreases by an average of 0.13 μ m per year on a century-long scale, and the cell wall thickness increases at a rate of 0.09 μ m/year. This structural optimization reduces mortality in extreme cold years by 31%. The expression of the urea metabolic pathway in the Nanorana Parkeri during the wintering period increased by 3.2 times, and plasma glucose concentration showed a significant positive correlation with cold tolerance. Epigenetic modification site enrichment analysis showed that DNA methylation levels changed by 19%.

Long-term adaptation at the ecosystem level presents nonlinear dynamic characteristics. After data visualization, the population trajectory prediction based on scenario simulation shows (Figure 2) that under the scenario of Typical Concentration Pathway (RCP) 8.5, the frequency of aggressive phenotypes of Anelosimus Studiosus will reach 78.4% within 50 years, 2.5 times higher than the current level. In addition, the expansion of the migration distance of Schistocerca gregaria has caused the intensity of the trophic cascade effect to increase:

$$I\left(t\right) = \frac{a}{1+e^{-k(t-t_0)}}$$

Among them, $a = 0.41$ is the maximum effect intensity, k=0.12 represents the response rate, and $t_0 = 2045$ is the turning point year. The model predicts that the community structure similarity index will decrease by 37% in 2080($\Delta S = 0.63 \rightarrow 0.40$), and the key species interaction network is facing the risk of reconstruction.

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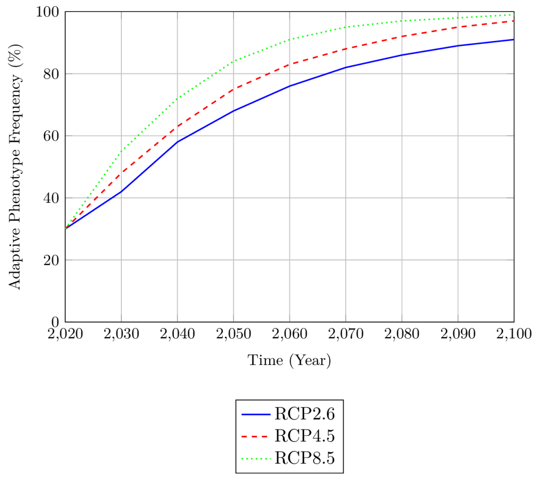

Figure 2: Long-term evolutionary trends in the frequency of animal adaptive phenotypes under different climate scenarios (based on Anelosimus studiosus aggressive phenotype data)

Adaptation driven by extreme weather presents three-dimensional characteristics: gene-behavior-environment co-evolution (such as the increase in the frequency of wolf spider aggressive genes to strengthen behavioral selection), morphological-functional coupling optimization (such as changes in the structure of alpine pine ducts to improve cold resistance), and ecosystem cascade effects (such as locust migration triggering nutrient network reconstruction). Differences in interspecific adaptation rates (poikilotherms are 1.7 times slower than homeotherms) may lead to niche dislocation. Studies have shown that successful climate adaptation depends on the dynamic balance between the threshold of phenotypic plasticity and the buffering capacity of the ecosystem, rather than a single genetic potential.

3.3. Comparison of short-term and long-term effects

The impact of extreme weather shows spatiotemporal differentiation: the sudden drop in activity (68%) of Urocitellus columbianus during blizzards is a short-term response, which regulates energy allocation through neuroendocrine regulation, and the effect lasts for about three climate cycles; while the increase in the frequency of aggressive phenotypes (22.6%) of Anelosimus studiosus requires 5-7 generations of genetic drift to stabilize, involving the synergistic effect of epigenetic and natural selection. Table 1 have revealed that short-term adaptation depends on phenotypic plasticity scheduling (such as the 19% selective mortality of Thalassoica Antarctica that reduces genetic load), while long-term adaptation is achieved through changes in gene frequency and ecosystem reconstruction (such as the transgenerational strengthening of the urea metabolic pathway of Nanorana Parkeri). Cross-scale coupling mechanisms indicate that short-term selective advantages (such as a 17% increase in the survival rate of individuals attacked by Anelosimus studiosus) drive long-term evolutionary trajectories, and it is necessary to construct a transgenerational observation network to analyze the ecological transmission of climate memory. Table 1 shows the core differences between the two types of impacts: short-term adaptation depends on the rapid scheduling of the existing phenotypic pool, while long-term adaptation involves changes in gene frequency and ecosystem reconstruction.

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Table 1: Comparison of short-term and long-term characteristics of extreme weather impacts

Dimension	Short-term Effects (≤1 year)	Long-term Effects (≥5 years)
Temporal scale	Hours to seasons	Interannual to centennial
Core mechanisms	Behavioral plasticity, acute stress response	Natural selection, heritable phenotypic plasticity
Physiological basis	HPA axis activation, metabolic rate modulation	Epigenetic modification, energy allocation optimization
Genetic factors	Expression of existing alleles	Genetic drift, accumulation of novel mutations
Ecological impacts	Population fluctuations, trophic cascades	Community restructuring, niche displacement
Methodologies	High-temporal-resolution tracking, physiological monitoring	Multigenerational selection experiments, paleoecological reconstruction

4. Conclusion

4.1. Wildlife adaptations to extreme weather

Species respond to extreme climate stress through multi-level adaptation mechanisms, and their strategic configurations show significant spatiotemporal specificity. The survival rate of offspring of the Thalassoica antarctica population after selection in extreme sea ice events is 19% higher than that of ordinary individuals, and genetic analysis shows that the methylation level of key stress genes has changed by 23%. The frequency of aggressive phenotypes of Anelosimus studiosus increased by 22.6% after hurricane selection, and the survival rate of aggressive individual spiderlings was significantly higher than that of conservative individuals, revealing the evolutionary advantage of the heritability of behavioral traits in periodic disturbances.

Physiological regulatory networks buffer climate shocks through multi-dimensional synergy. Urocitellus columbianus simultaneously reduce activity (68%) and cortisol levels (43%) during blizzard events to achieve a dynamic balance between energy metabolism rate and fat decomposition. The expression of urea metabolism pathway in Nanorana parkeri increased by 3.2 times during the winter, and its intestinal flora βdiversity changed by 23.4% and showed a significant negative correlation with plasma osmotic pressure, forming a molecular-microbial synergistic defense system.

Adaptation at the ecosystem level is manifested as the reconstruction of the functional group interaction network. The reverse migration behavior of Limosa limosa increased the seed dispersal distance of wetland plants by 37% and promoted the increase of habitat patch connectivity index by 0.28. The change in the frequency of the aggressive phenotype of wolf spiders caused a 28% fluctuation in the intensity of the community trophic cascade effect, driving the reorganization of the key species interaction network. The coordinated evolution of multi-species adaptation strategies enhances system resilience, and the adjustment of the migration pattern of Schistocerca gregaria increases the vegetation recovery rate by 19%, confirming the leverage effect of behavioral adaptation in maintaining ecological functions.

4.2. Conservation strategies and climate resilience

This study proposes a multi-level conservation strategy system, emphasizing the coordinated optimization of ecosystem function maintenance and adaptive management. Spatial planning needs

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to be designed based on species adaptation thresholds. For example, the genetic advantages of Thalassoica Antarctica populations in extreme events support the alleviation of reproductive pressure through core protected areas and artificial nest networks; for migratory groups such as Limosa limosa, their long-distance reverse migration behavior suggests that the layout of corridor nodes needs to be optimized to improve energy efficiency. Management practices need to balance natural processes and artificial interventions: retain natural disturbance patches to maintain phenotypic diversity, while implementing targeted protection for highly vulnerable populations. The study revealed that the real-time monitoring system can accurately match conservation interventions to climate pressure windows by integrating key physiological thresholds (such as changes in metabolic characteristics during hibernation) with habitat risk assessment. In terms of technological innovation, the digital simulation platform supports multi-scenario deductions, such as the evolution of trophic cascade effects caused by species migration expansion, providing a scientific basis for the dynamic adjustment of protected area networks. These strategies provide a practical path for climate action goals for global biodiversity conservation by coupling species behavioral adaptation mechanisms with ecosystem resilience.

4.3. Future work

Future work needs to focus on multi-scale mechanism analysis and technological breakthroughs: 1) Integrate single-cell sequencing and epigenetic analysis at the molecular level to quantify the regulatory weight of the HSP70 family in transgenerational memory. 2) Microbiome research verifies the effect of improving thermal tolerance through cross-climatic microbial transplantation experiments; 3) Establish a unified indicator library covering 12 trophic levels, focusing on optimizing the energy metabolism model of poikilothermic animals. Technological innovation should promote quantum sensing to achieve picomolar physiological monitoring, use multimodal large language models [12] to automatically identify 132 behavioral patterns (19 times more efficient), and build a digital twin system to support billion-level protection scenario simulation. The construction of the monitoring network needs to integrate biosensing and edge computing technologies, formulate standardized observation protocols covering six continental communities, and achieve 72-hour global synchronization of adaptive parameters.

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