

Research Report

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Exploring the Diversity of Gene Expression in Superspecies Driven by Environmental Adaptation

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Abstract Superspecies are one of the eye-catching concepts in biodiversity research, representing highly related species groups that typically exhibit extensive ecological and genetic diversity. This study focuses on the gene expression diversity of superspecies and explores the key role of environmental adaptation in their diversity formation process. It also introduces the concept and evolutionary mechanism of superspecies, emphasizing their prominent characteristics in ecological adaptation. Through in-depth research on the definition, importance, and close correlation with environmental adaptation of gene expression diversity, this study elaborates on the application of modern genomics and transcriptomics technology in this field, as well as future research directions, including the evolutionary mechanism of gene expression diversity and the long-term impact of environmental changes on superspecies. The importance of gene expression diversity driven by environmental adaptation in the function and niche differentiation of ecosystems is particularly important, providing a scientific basis for the protection and management of these biological resources.

Keywords Super species; Gene expression diversity; Environmental adaptation; Niche differentiation; Conservation biology

Superspecies are a prominent concept in the field of biology, describing a group of highly related species that typically exhibit excellent adaptability in complex ecosystems (MacArthur and Wilson, 1963; Fang, 2023). These species populations have similar morphological, ecological, and genetic characteristics, but may exhibit significant adaptive differences under different environmental conditions. The concept of super species has sparked widespread scientific interest as they provide powerful examples for understanding species evolution and ecological adaptation.

In the study of superspecies, gene expression diversity has become a topic of great concern. Gene expression diversity involves changes in the expression levels of different genes between individuals or populations, which is an important component of genetic diversity. For super species, research on gene expression diversity can reveal the molecular mechanisms of environmental adaptation and help explain why closely related species exhibit different ecological characteristics in different environments.

The purpose of this study is to summarize and delve into the research progress of gene expression diversity driven by environmental adaptation in super species, focusing on the special biological population of super species and exploring the relationship between their gene expression diversity and environmental adaptation. Specifically, we will investigate how gene expression diversity plays a role in the evolution of superspecies and how it affects species adaptability and niche differentiation. By synthesizing existing research results, the aim is to provide a deeper understanding and scientific basis for the origin of biodiversity and species interactions in ecosystems, which helps to better protect these special biological groups and the ecosystems they reside in.

1 Definition and Evolution of Superspecies

1.1 Concept and origin of superspecies

Superspecies are a prominent concept in the field of biology, representing highly related populations of species that typically have similar external morphology and ecological habits (Fang, 2023). This concept was first proposed by ecologist E. O. Wilson proposed in 1963 to describe species that are related but still capable of hybridization with each other (MacArthur and Wilson, 1963). The formation of super species is usually related to

geographical isolation and ecological adaptation. In the past few decades, research on superspecies has expanded to include plants, insects, birds, and other biological populations (Figure 1).



Figure 1 A certain insect of a superspecies

The origin of superspecies usually involves a series of evolutionary events, including species differentiation, maintenance of genetic relationships, and ecological adaptation. Species differentiation may be due to geographical isolation, such as the formation of mountains or water bodies, leading to the formation of different related species. Over time, these species may have adapted to different niches in different ecosystems, thereby maintaining their genetic relationships.

1.2 Evolution mechanism of superspecies

The evolutionary mechanism of super species is multi-level, involving the interaction of genetic and ecological factors. An important evolutionary mechanism is the maintenance of kinship, which is usually related to reproductive isolation between species. The reproductive isolation mechanism can prevent hybridization between different related species and help maintain the independence of related species. In addition, gene flow restriction is also a key factor in the evolution of superspecies, which can reduce gene exchange between different species.

Ecological adaptation is another key factor affecting the evolution of superspecies. Different species may adapt to different niches in different ecosystems, which helps maintain their genetic relationships. For example, the same related species may develop different predatory strategies or food selection habits in different ecosystems to reduce resource competition.

1.3 Characteristics and ecological adaptability of super species

The characteristic of super species is that they have a high degree of kinship, but still have ecological and genetic diversity. This diversity enables super species to survive and reproduce in complex and ever-changing ecosystems. They usually live in similar habitats, but may occupy different ecological niches to reduce competitive pressure.

Ecological adaptability is a significant characteristic of super species (Zhang et al., 2019). These species often exhibit excellent adaptability in their respective ecosystems, including adaptation to environmental conditions, clever resource utilization, and strategies for predation or avoidance. This ecological adaptability helps them survive in highly competitive ecosystems and maintains their genetic relationships.

2 Environmental Adaptation and Gene Expression Diversity

2.1 Concept and importance of gene expression diversity

Gene expression diversity refers to the differences in gene expression levels between different individuals within the same species or under different environmental conditions. This difference can include the intensity, timing, and location of gene expression, as well as the rate of protein synthesis. Gene expression diversity is widely present in organisms, reflecting the functional diversity of genes and their adaptability to different environments (Chen, 2021).

The importance of gene expression diversity cannot be underestimated. It is an important form of biodiversity that contributes to the adaptability and evolution of species. Through gene expression diversity, different individuals can exhibit different adaptive characteristics when facing different environmental challenges, which contributes to the diversity and stability of species in ecosystems. In addition, gene expression diversity is also related to diseases and health conditions, which can affect an individual's disease resistance and adaptability.

2.2 The impact of environmental adaptation on gene expression

Environmental adaptation is one of the main driving forces for gene expression diversity (Zhang et al., 2019; Qin et al., 2021). Organisms must adjust their gene expression under different environmental conditions to adapt to changes in the environment. This adaptive adjustment can occur on both short-term and long-term time scales.

On a short-term time scale, environmental changes can quickly trigger changes in gene expression. This rapid response usually involves the activation and inhibition of genes to adapt to exposure to environmental stimuli. For example, in the face of ultraviolet radiation, certain organisms can quickly adjust the gene expression of epidermal cells to increase the protective ability of the skin.

On a long-term time scale, environmental adaptation can lead to the evolution of gene expression diversity. When species live in different ecosystems, they may gradually accumulate adaptive genotypes, leading to differences in gene expression patterns. This difference can involve the coordinated regulation of multiple genes to achieve better adaptability.

2.3 Mechanisms of gene regulation and expression polymorphism

Gene regulation is one of the key mechanisms controlling gene expression diversity. The expression of genes is controlled by a series of regulatory elements and protein interaction networks. These regulatory elements include promoters, enhancers, transcription factors, etc., which work together to regulate gene expression levels.

Mutations in the genome can affect the coding sequence or regulatory elements of genes, leading to differences in expression between individuals or species. These mutations can include single nucleotide polymorphism (SNP) or insertion/deletion. DNA methylation is an epigenetic regulatory mechanism that can silence or activate genes through methylation (Shi et al., 2013). DNA methylation patterns under different environmental conditions can lead to gene expression diversity. Transcription factors and miRNAs are important molecules in gene expression regulation, which can interact with specific gene promoters or mRNA molecules, thereby affecting gene expression levels.

In the context of environmental adaptation, these mechanisms may interact with each other, leading to the generation of gene expression diversity. Through these mechanisms, organisms can adjust gene expression under different environmental conditions to adapt to external pressures and resource utilization needs.

3 Study on Gene Expression Diversity of Three Superspecies

Studying the diversity of gene expression in super species is a crucial step in understanding their adaptability and evolutionary processes. By conducting case studies, exploring the role of gene expression diversity in evolution, and applying genomics and transcriptomics methods, we can better understand the ecological adaptability and driving mechanisms of diversity of superspecies.

3.1 Case study on gene expression diversity of superspecies

Darwin's Finches are a group of finch species on the Galapagos Islands, used to study how gene expression diversity drives ecological differentiation of species. Research has found significant differences in mouth shape and food feeding strategies among Darwin finches on different islands, which are closely related to their gene expression patterns. Through transcriptomics and gene expression analysis, scientists have identified genes related to mouth shape and food type, and the expression differences of these genes lead to differences in ecological adaptability among different individuals (Figure 2).

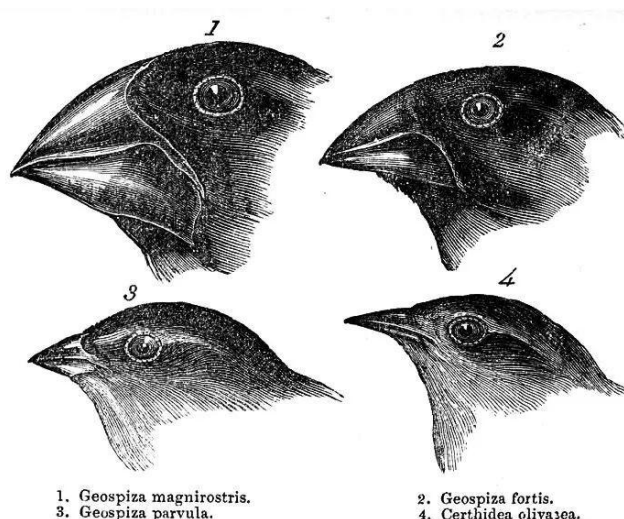


Figure 2 Mouth shape and food type

African Cichlid Fish is a group of fish found in African lakes, used to study how gene expression diversity drives ecological adaptation of species. Different types of African cichlid fish have developed different body sizes and feeding strategies in different lakes. By analyzing their gene expression patterns, researchers discovered genes related to body size and food type, and the differential expression of these genes helps them survive in different ecological niches.

Swordtail fish are a group of fish that live in the Caribbean Sea, including multiple different species of Swordtail fish. These fish live in different water bodies, some in freshwater environments, while others live in saline environments. By studying their gene expression, scientists have found significant differences in gene expression between freshwater and saline environments. These differences include genes related to saltwater adaptability, such as sodium pump genes, and genes related to food types, which help different swordfish adapt to the type of water they live in.

3.2 The role of gene expression diversity in the evolution of superspecies

Gene expression diversity plays an important role in the evolution of superspecies. It can promote species adaptability and niche differentiation, thereby maintaining genetic relationships and promoting species diversity (Han et al., 2022).

Gene expression diversity can lead to different individuals or subspecies exhibiting different ecological adaptive characteristics in different niches. This difference can involve life history strategies, food intake patterns, and responses to environmental changes. By adapting to different ecological conditions, individuals within superspecies can reduce competitive pressure and better coexist. For example, individuals with different mouth shapes in Darwin finches can occupy different food resources on the same island, thereby reducing competitive pressure.

The diversity of gene expression can increase the adaptability of species to environmental changes. Under different environmental conditions, individuals can exhibit different gene expression patterns to adapt to new challenges. When super species face pressures such as climate change, new competitors, or habitat loss, gene

expression diversity allows individuals to quickly adapt to new challenges. This contributes to the survival and successful reproduction of the species.

3.3 Application of genomics and transcriptomics methods in research

Studying the diversity of gene expression in superspecies typically requires the use of advanced genomics and transcriptomics methods to reveal complex patterns of gene expression.

Genomics methods can help researchers identify genetic differences and gene families in superspecies. Comparative genomics research can reveal the evolutionary history and amplification patterns of gene families, which is crucial for understanding the genetic and functional diversity within superspecies. In addition, genomics methods can also help identify candidate genes related to ecological adaptability. Genomics methods can help researchers identify genetic differences and gene families in superspecies.

Transcriptomics methods allow researchers to analyze gene expression patterns in different individuals or species. By using high-throughput RNA sequencing technology (RNA Seq), genes with significant differences in expression under different environmental conditions can be identified. By comparing transcriptome data, genes related to ecological and environmental adaptation can be identified. In addition, transcriptomics methods can also help reveal gene regulatory networks and signaling pathways, thereby gaining a deeper understanding of the regulatory mechanisms of gene expression diversity.

4 Ecological Significance of Gene Expression Diversity Driven by Environmental Adaptation in Super Species

The diversity of gene expression in super species plays an important role in ecological significance. It affects the survival and reproductive success of species, promotes niche differentiation, and shapes the functionality and stability of ecosystems. Understanding how gene expression diversity interacts with ecological adaptability and niche differentiation can help better understand the role and evolutionary process of superspecies in ecosystems (Zhang et al., 2019; Fu et al., 2021).

4.1 The relationship between gene expression diversity and species survival and reproduction

Gene expression diversity plays a crucial role in the ecological significance of superspecies (Han et al., 2022). It directly affects the survival and reproductive success of species, as well as their ability to respond to environmental changes.

The diversity of gene expression can provide individuals within superspecies with more survival opportunities under different environmental conditions. Turdidae family of birds, such as *Horornis acanthoides* and *Urosphena squameiceps*, are distributed in different geographical regions and live in various habitats.

Individuals of tree warblers may exhibit different gene expression patterns in different habitats and climatic conditions. For example, the scaled tree warbler may exhibit different gene expression characteristics in cold northern habitats and warm southern habitats to adapt to different temperatures and food availability (Figure 3). This difference in gene expression helps them survive in their respective habitats and improves their chances of survival under specific environmental conditions.

The diversity of gene expression is also closely related to reproductive success. Under different environmental conditions, individuals can exhibit different reproductive strategies, including adjustments to the reproductive season, changes in reproductive behavior, and adjustments to reproductive investment. Tree warblers also exhibit different reproductive strategies. They may choose different breeding opportunities and methods in different seasons and geographical regions. For example, some tree warblers may breed in the summer of the north, while in the winter of the south, they choose different strategies. This diversity of gene expression helps them adjust their reproductive behavior based on local climate and resource availability, increasing the chances of successful reproduction.



Figure 3 *Urosphena squameiceps* is in different habitats in different seasons

4.2 Ecological adaptability and niche differentiation

Gene expression diversity is also closely related to ecological adaptability and niche differentiation, which is crucial for maintaining species diversity and niche stability (Zhang et al., 2019; Fu et al., 2021).

The diversity of gene expression can promote the ecological adaptability of super species. Under different environmental conditions, individuals can exhibit different ecological adaptability characteristics, such as food selection, habitat utilization, and competitive strategies. Darwin's finches, a group of birds on the Galapagos Islands, are considered classic examples of superspecies due to long-term natural selection and adaptation to different environmental conditions.

These birds live on different islands and ecological environments in the Galapagos Islands, and therefore need to adapt to different food resources and habitat conditions. Darwin's sparrows may exhibit different ecological adaptability characteristics on different islands. Some island finches may develop longer mouths to accommodate the consumption of large nuts, while others may have shorter mouths to accommodate the consumption of insects. This diversity of gene expression enables them to survive and reproduce on different islands, and effectively utilize available food resources.

Diversity in gene expression contributes to niche differentiation, reducing resource competition and niche overlap between species. Different individuals or subspecies can exhibit different niche characteristics, such as life history strategies, food intake patterns, and spatial utilization. Darwin's sparrows also exhibit differentiation in their birth positions on various islands. They choose different foods and habitats on different islands to reduce resource competition. This differentiation helps different subspecies coexist in the same ecosystem, maintaining their genetic relationships.

4.3 Impact of ecosystem function and stability

Gene expression diversity can affect the way superspecies participate in ecosystem functions (Fu et al., 2021; Han et al., 2022). Different individuals or subspecies may play different roles in ecosystems, such as at different levels of the food chain, as pollinators or predators. Superspecies in coral reef ecosystems, including different types of corals. Coral reefs provide ecosystem services such as providing habitats, food resources, and protecting coastlines. Different types of corals may play different roles in these functions. Some coral species may be more suitable as habitats, providing habitats and shelters, while others may be more suitable for providing food resources to support the food chain of marine ecosystems.

The diversity of gene expression is also related to the stability of ecosystems. The higher the diversity, the more likely the ecosystem is to resist external disturbances and environmental changes. Gene expression diversity can

increase the adaptability and survival opportunities of species in ecosystems, thereby improving the stability of ecosystems. Different types of corals may exhibit different forms and growth strategies, enabling them to occupy different ecological niches. Some coral species may be more adapted to shallow water environments, while others are more adapted to deep water environments. This diversity of gene expression helps different types of corals collaborate in coral reefs, jointly maintaining the diversity and stability of ecosystems.

5 Conclusion and Outlook

The diversity of gene expression in super species driven by environmental adaptation is a key factor in biodiversity. By diversifying gene expression, superspecies can adapt to different environmental conditions, resource utilization strategies, and niche differentiation, thereby improving their survival and reproduction success rates. This diversity helps to maintain the diversity and stability of ecosystems, promoting the maintenance of ecological functions. The diversity of gene expression in super species reflects the results of natural selection and adaptation, and is an important component of ecological and evolutionary processes.

Future research can explore in more detail the evolutionary mechanisms and genetic regulation of gene expression diversity. This includes understanding how different gene expression patterns evolve and maintain in superspecies. Research can focus on the effects of genome level variation, mutation accumulation, and natural selection on gene expression diversity (Shi et al., 2012). In addition, the roles of non coding RNA, epigenetics, and epigenetic regulation in gene expression diversity can be studied to gain a deeper understanding of this complex biological phenomenon.

With the continuous development of technology, future research can utilize advanced genomics, transcriptomics, and bioinformatics tools to more comprehensively study gene expression diversity (Shi et al., 2012). New technologies such as single-cell RNA sequencing, proteomics, and metabolomics can provide more data layers to help reveal the mechanisms and functions of gene expression diversity. In addition, machine learning and artificial intelligence methods can help analyze and interpret large-scale gene expression data, deepening understanding of superspecies.

Superspecies play a crucial role in maintaining ecosystem functionality and stability. Therefore, protecting and managing these species is crucial for the health of ecosystems. This review emphasizes that gene expression diversity, as a key component of the adaptability of super species, is crucial for their survival and ecosystem function. Protecting superspecies in ecosystems requires comprehensive consideration of gene expression diversity to ensure the maintenance of their genetic diversity and adaptability.

Overall, the diversity of gene expression in super species driven by environmental adaptation is an important research topic in the fields of ecology and evolutionary biology. Further research on this phenomenon will help us better understand the operational mechanisms of ecosystems, protect biodiversity, and address the challenges posed by environmental change. Through continuous efforts, we can better protect and manage super species in ecosystems, providing scientific basis for future research work.

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