

Interrelationships among Species in Ecosystems and Their Impact on Environmental Adaptation: A Review

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Abstract. *Picea asperata* is a plant species unique to China, with its populations distributed across multiple ecosystems, ranging from northern boreal forests to alpine ecosystems such as the Qinghai-Tibet Plateau. Due to its extensive distribution across diverse environments, understanding the adaptation of *Picea asperata* to these varied environmental conditions has become an important scientific research issue. Thus, the paper aims to explore the complex interrelationships within *Picea asperata* species complex and their impact on environmental adaptation. Through a review and analysis of recent genomic research, the study examines the combined effect of gene flow, phylogenetic relationships, and adaptive evolution on the survival and evolution of these species. The results show that 20,808 environment-related genes and four distinct gene flow patterns contribute to the remarkable adaptability of the *Picea asperata* populations across different ecosystems in China. It may offer useful insights into the mechanisms of species adaptation, thus serving as a reference for forest ecosystem conservation in the context of global climate change.

Keywords: *Picea Asperata* Complex, Species Interrelationships, Gene Flow, Environmental Adaptation, Ecological Genomics

1. Introduction

The *Picea asperata* complex includes eight distinct spruce species distributed across a broad range of environments, from northeastern China to the Qinghai-Tibet Plateau, offering an ideal model for studying species adaptation and evolution. These species adapt to different ecological environments through gene flow and genetic exchange. Prior studies have identified 20,808 genes associated with environmental changes, highlighting the role of genes in adaptation [1]. Furthermore, transposable elements play a key role in genetic variation and species adaptation [2]. This study aims to integrate the latest findings in genomics and ecology to explore the classification and nature of interspecies relationships within the *Picea asperata* complex. In particular, it investigates the ways interspecific relationships influence ecological functions and species adaptation in forest ecosystems, elucidating how both antagonistic and mutualistic interactions maintain ecosystem stability and determining the importance of gene flow and genetic exchange for adaptation to varying habitats. By reviewing recent literature, it seeks to examine species adaptation mechanisms, particularly survival strategies across ecological gradients, and explore how gene flow and genetic exchange contribute to these processes, which may provide new insights for biodiversity conservation and ecological restoration.

2. The concept and classification of species interrelationships

2.1. The definition of species interrelationships

In a shared habitat, species interact in ways that affect their survival, reproduction, and evolution, including competition, cooperation, predation, symbiosis, as well as parasitism. The competition for limited resources among species drives adaptive evolution, often resulting in the differentiation of ecological niches. For example, studies on the *Picea asperata* complex have indicated that species within this group have developed distinct competitive relationships through adaptive evolution, responding to different environmental conditions [2]. By supporting one another, species can boost their survival, especially in times of resource scarcity, through cooperation. In some cases, species share resources or provide mutual assistance through symbiotic relationships. For instance, some plants form symbiotic relationships with mycorrhizal fungi, helping them absorb more nutrients, which not only promotes growth but also strengthens their environmental adaptability [3]. Predation influences the evolution of species by driving the development of defensive mechanisms in prey species, such as toxins or camouflage, to improve their chances of survival. Symbiotic relationships foster mutual dependence and promote adaptive traits in species, where cooperation offers survival advantages. In contrast, parasitism depends on the host for survival, often causing harm, and drives the co-evolution of both the parasite and the host. And these interactions shape species' adaptability, distribution, and ecological roles, sustaining ecosystem balance.

2.2. The classification of species interrelationships

In the *Picea asperata* complex, the interrelationships among species are mainly impacted by gene flow, competition, cooperation, and hybridization, all of which play a role in species differentiation and adaptation. Phylogenetic tree analysis reveals five distinct clades within the complex, with *P. wilsonii* and *P. neoveitchii* representing early divergence events, while the other species exhibit closer genetic relationships [2]. These phylogenetic trees reflect genetic differences between species and provide a basis for understanding species evolution. By facilitating genetic exchange, gene flow plays a key role in adaptive evolution, influencing both species distribution and their ability to adapt. For instance, drought-resistant genes from *P. crassifolia* are transferred to *P. asperata*, enhancing its survival ability in arid regions [4]. Gene flow promotes gene sharing among species but can slow down species differentiation, maintaining a high level of genetic similarity. The distribution and resource utilization of species within the complex are shaped by competition and cooperation. As species compete for light, water, and nutrients, they are driven to develop specialized adaptations. For example, *Picea asperata* adjusts its root structure in low-light environments to improve water and nutrient absorption, showing adaptation differences from other species. Meanwhile, cooperative interactions between species, such as the symbiotic relationship between *Picea asperata* and fungi, help boost adaptive capacity by enhancing nutrient uptake and supporting growth in nutrient-poor soils. Hybridization plays an important role in the complex by complicating gene flow between species, potentially introducing new gene combinations that provide opportunities for adaptive evolution. Hybrid offspring often exhibit adaptive traits inherited from different parent species, such as enhanced cold tolerance, suggesting that hybridization can provide new adaptive capacities, improving species survival in different environments [5].

3. Ecological functions of species interrelationships

3.1. The role of species diversity in ecosystem stability

The *Picea asperata* complex exemplifies how species diversity boosts ecosystem stability. Previous studies have demonstrated that each species within the complex contains a substantial number of environment-related genes, forming a genetic reservoir that reinforces the resilience of the forest ecosystems they occupy [2]. Each species fulfills a specific ecological role in adapting to its environment. Despite evolutionary divergence, they maintain gene flow and genetic connectivity. The genetic material of certain species can be passed to others through gene flow, thus enhancing the adaptive potential of the entire complex. For example, genes from more distantly diverged species can introduce new adaptive traits to other species within the complex, aiding their ability to cope with environmental pressures like climate change or habitat disruption. Species diversity also strengthens ecosystem resilience by increasing functional redundancy. With the collective actions of different species, an ecosystem can maintain its essential functions even when some species are impacted by environmental stressors, as other species fill their ecological niches. For example, while climate warming may harm some species, the diversity within the complex enables others to better tolerate rising temperatures or adapt to changes in precipitation. Also, the genetic differences among species ensure that the ecosystem can find adaptive pathways under varying environmental conditions, thereby maintaining the stability and productivity of ecosystem functions. It is found that the diverse species within the *Picea asperata* complex improve the forest ecosystem's ability to maintain productivity under changing temperature and precipitation regimes in the context of climate warming [3]. Different species respond differently to climate change, with some showing greater tolerance to increased temperatures and others adapting better to changes in precipitation. The diversity of species adaptations provides stability to the forest ecosystem, thus enabling it to function effectively under fluctuating environmental conditions. Genetic diversity offers flexible adaptation mechanisms, ensuring the maintenance of ecosystem functions amid climate change and environmental disturbances.

3.2. The energy flow and nutrient cycling in forest ecosystems

Through species-specific physiological adaptations, the *P. asperata* complex plays a crucial role in the functioning of forest ecosystems by contributing to energy flow and nutrient cycling. Genomic analysis has revealed that each species has evolved unique physiological traits that influence their interactions with the environment. Different species exhibit varying efficiencies in carbon fixation and storage, which impact the overall carbon sequestration capacity of the forest ecosystem. For example, some species may possess genes that enable them to fix carbon more efficiently under specific light or temperature conditions. This contributes to the overall carbon storage capacity of the forest. Studies have shown that *Picea asperata*, in its native mountainous habitats, possesses specific genes that regulate the activity of key photosynthetic enzymes, optimizing carbon fixation under the light and temperature profiles of its environment. These genes help *Picea asperata* capture and store more carbon dioxide during the day, which is essential for maintaining the carbon balance in the forest ecosystem. In addition, species-specific genes involved in water-use efficiency and drought response also play a significant role in nutrient and water cycling in the ecosystem. For example, some species may have genes that allow them to conserve water during dry periods, while others are better adapted to wetter environments. In a study on the water-use strategies of *Picea* species in arid and semi-arid regions, it was found that *P. crassifolia* has genes related to deeper root

growth and more efficient water-uptake mechanisms, allowing it to survive in drier soils. *Picea asperata* may also possess a unique set of genes that regulate water usage, such as genes controlling the opening and closing of stomata to reduce water loss under drought conditions. These genes help species maintain growth and reproduction under varying water availability conditions, which affects nutrient and water cycling across the ecosystem. In terms of nutrient cycling, species-specific root characteristics contribute to nutrient uptake and soil stabilization. The roots of different species may vary in structure or secrete different compounds that influence nutrient availability and soil structure stability. For example, *Picea asperata* roots release specific organic acids that increase phosphorus solubility in the soil, thereby enhancing nutrient uptake efficiency [4]. The study on the low-order fine roots of *Picea asperata* and their responses to seasonal soil freezing and freeze-thaw cycles further illustrates how root-soil interactions are impacted by environmental factors, affecting nutrient cycling and soil stability [6]. The growth and development of low-order fine roots are influenced by soil temperature and moisture, which affect nutrient uptake and interactions with soil microorganisms, ultimately playing a vital role in maintaining soil health and supporting nutrient cycling. Besides, the role of different species in energy flow and nutrient cycling underscores their complementary ecological functions. Through unique physiological traits and genetic adaptations, species contribute significantly to maintaining ecosystem stability and enhancing productivity. For example, in processes such as photosynthesis, carbon fixation, water use, and nutrient uptake, the adaptive features of different species complement each other, ensuring the forest ecosystem remains productive and stable under changing environmental conditions.

3.3. The self-regulation mechanism and ecological balance

The *P. asperata* complex demonstrates complex self-regulation mechanisms that sustain ecological balance. These mechanisms allow species to adjust their growth, reproduction, and resource use in response to environmental pressures, thereby ensuring population stability and the maintenance of ecosystem functions. Through specific gene expression patterns, genomic evidence illustrates how species within the complex adapt to environmental changes. Under stress conditions like drought or temperature extremes, certain genes are either up-regulated or down-regulated to slow growth or reproduction. And this adaptive response allows species to conserve resources and endure adverse conditions, maintaining population stability across a range of environments. For example, a study on the drought response of *Picea asperata* found that genes associated with growth hormones were down-regulated under drought stress [2]. This reduction in growth rate serves as a self-regulatory mechanism, helping conserve water and other essential resources during periods of water scarcity. By slowing growth, *Picea asperata* ensures that available resources are utilized more efficiently, helping the species survive under challenging conditions. This type of self-regulation not only aids the survival of individual species but also contributes to the balance of the broader ecosystem by preventing resource depletion. In addition to genetic adjustments, species within the complex also engage in interactions that regulate population sizes and maintain ecological stability. For example, some species may suppress the growth of others through competition for limited resources, such as light, water, or nutrients. These competitive interactions regulate population densities, preventing any single species from dominating the ecosystem and ensuring that resources are allocated in a way that supports biodiversity. In contrast, some species may modify habitat conditions, creating environments that support the growth of other species, thereby maintaining a dynamic balance in the ecosystem. The self-regulation mechanisms within the *P. asperata* complex are also tightly connected to the species' capacity to adjust to shifting environmental conditions. For instance, *Picea asperata*, like other species in the complex, can adjust its distribution and reproductive strategies in

response to shifts in climate or habitat. If environmental conditions become less favorable in one area, the species may migrate to a more suitable location or alter its reproductive timing to ensure successful offspring production. These adjustments help the complex maintain balance, adapt to challenges, and preserve ecosystem functionality.

4. The impact of species interrelationships on environmental adaptation

4.1. Environmental adaptation mechanisms of the *Picea asperata* complex

In response to environmental pressures like climate change and soil variations, the *Picea asperata* complex has developed a variety of adaptive strategies that are crucial in shaping species evolution. These species have developed specialized traits to tackle diverse environmental challenges, thus showcasing remarkable ecological flexibility. For example, *Picea asperata* has developed drought resistance and tolerance to poor soil conditions, which are essential for survival in diverse habitats ranging from moist, nutrient-rich soils to dry, nutrient-poor environments. These adaptive strategies have led to the differentiation of species within the complex, each occupying a unique ecological niche shaped by its distinct traits. In recent years, genomic studies have provided deeper insights into the genetic mechanisms underlying these environmental adaptations. Key genes associated with stress resistance like those that control drought tolerance and nutrient uptake, have been identified as crucial factors enabling the species to thrive in diverse environmental conditions. In addition, these genes often show evidence of gene flow between species within the complex, suggesting that adaptive traits are not only inherited but also exchanged between species, further accelerating the adaptive evolution process. And these findings highlight the role of genetic diversity in helping the *Picea asperata* complex adapt to changing environments.

4.2. Inter-species cooperation and its role in adaptive evolution

In the *Picea asperata* complex, cooperation between species is crucial for adaptive evolution. The adaptive capacity of species is significantly enhanced by symbiotic relationships, such as the one between *Picea asperata* and fungi. The symbiotic relationship enhances nutrient uptake, particularly in nutrient-poor soils, which is crucial for the survival and growth of these species in challenging environments. Through mutualistic partnerships, species in the complex are better equipped to withstand environmental stressors like low soil fertility and limited water availability. Gene flow is an integral part of these cooperative interactions, as it allows for the exchange of adaptive genes between species. For instance, beneficial genes related to nutrient absorption, drought resistance, and disease resistance can be transferred through symbiotic relationships, allowing species to quickly adapt to changing environmental conditions. This gene flow not only facilitates the spread of advantageous traits but also accelerates adaptive evolution, helping species to respond more effectively to environmental changes. In environments where resource availability is unpredictable, cooperation between species enhances their collective resilience. These interactions, combined with the transfer of adaptive genes, allow species to survive and thrive in diverse and fluctuating habitats. The cooperation accelerates the adaptive evolution of the *Picea asperata* complex, thus ensuring its survival across a range of ecological settings.

4.3. Competitive pressures and selective evolutionary changes

In the *Picea asperata* complex, selective evolutionary changes are primarily driven by competitive pressures. The competition for essential resources such as light, water, and nutrients forces species

within this complex to develop specialized adaptations, hence improving their survival in specific ecological niches. This results in a selective sweep, where species with advantageous traits, such as improved drought resistance or better nutrient uptake, are more likely to thrive, while less-adapted species face challenges in maintaining their populations. Evidence suggests that competition has led to significant evolutionary changes in the *Picea asperata* complex. For example, species that are better adapted to low-light conditions have evolved specialized root systems or foliage that enable them to compete effectively for limited resources in shaded environments. Besides, some species have developed improved resistance to environmental stressors, such as pests or extreme weather conditions, as a result of competitive pressures. The evolutionary process driven by competition has resulted in distinct genetic variations and adaptive traits among the species within the complex. These adaptive changes are often visible in the morphological and physiological traits of the species, such as variations in root structure, leaf shape, as well as drought tolerance. These traits, shaped by competitive pressures, allow species to adapt to specific environmental conditions and make better use of available resources, ultimately boosting their survival and reproductive success.

5. Conclusion

The *Picea asperata* complex demonstrates remarkable environmental adaptability through its unique mechanisms of gene flow, competition, and cooperation. The interrelationships between species not only influence individual growth and reproduction but maintain the stability and functionality of the forest ecosystem on a broader scale. Genomic research reveals how species adapt to environmental pressures like drought and temperature changes via specific gene expression patterns, promoting adaptive evolution. These adaptive traits and self-regulation mechanisms enable the *Picea asperata* complex to sustain population stability and ecosystem productivity, even in the face of challenges such as global climate change. In addition, species diversity and the complementary ecological functions of these species are crucial to the stability of the forest ecosystem. Through gene flow and interspecies cooperation, the *Picea asperata* complex effectively adapts to environmental changes across ecosystems, supporting the sustained development of forest ecosystems. Future research on gene flow and environmental adaptation mechanisms in the *Picea asperata* complex can provide valuable insights for forest conservation and ecological restoration. By deepening our understanding of species adaptation, it may help address climate change and preserve ecosystems.

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