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The Impact of Introgression on the Maintenance of Genetic Diversity in Plants

Xinying Cao

Qide Star Society, Shanghai, China
cathy_cao0911@qq.com

Abstract: Introgression represents a key mechanism of gene flow between species, playing a critical role in the maintenance and enhancement of genetic diversity in plant populations. This paper examines the role of introgression in plant communities, with a main focus on its contribution to genetic diversity and its significance in evolutionary processes and adaptive responses. By synthesizing relevant literature, the genetic foundations of introgression, the mechanisms of gene flow, and the genetic stability of hybrid progeny are discussed. The results demonstrate that under conditions of environmental change and ecological pressures, introgression facilitates the acquisition of novel adaptive traits within species populations, thereby enhancing their survival and reproductive success. Furthermore, introgression plays an essential role in the conservation of endangered species, as gene flow serves to augment genetic diversity, which mitigates the detrimental effects of invasive species. Nevertheless, introgression can also lead to the blurring of species boundaries, potentially posing a threat to ecosystem stability. Thus, the paper suggests further investigation into the ecological and genetic consequences of introgression, in order to better understand its role in biodiversity conservation.

Keywords: Introgression, Genetic Diversity, Environmental Changes, Gene Flow, Adaptive Evolution

1. Introduction

Introgression, initially introduced by Anderson and Hubricht, refers to the repeated backcrossing of hybrid offspring with one or both of the parent species, gradually introducing specific traits into one parent species [1]. In recent years, significant progress has been made in the field of introgression research in botany, revealing its key role in the maintenance of genetic diversity, speciation, and adaptive evolution. Similar phenomena have also been observed in various animal groups, including insects, fish, amphibians, birds, and mammals [2]. There is clear evidence that introgression plays a significant role in the maintenance of genetic diversity in plants [3]. This paper aims to explore the role of introgression in the maintenance of genetic diversity, with a particular focus on the impact of environmental changes on this process. In particular, it analyzes the patterns of introgression across different ecosystems, examines how environmental pressures disrupt the introgression process, and identifies key factors that may contribute to the loss of genetic diversity. Thus, this paper explores the dynamic processes and potential impacts of introgression through a review of existing literature and relevant case studies. This research helps bridge the knowledge gap regarding the interactions

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between environmental changes and introgression, providing insights for biodiversity conservation, species management, and the sustainable development of ecosystems.

2. The Mechanisms of the Introgression in Plants

2.1. Drivers of Natural Hybridization

Natural hybridization refers to the genetic exchange and interbreeding between two or more distinct populations in their natural habitats, driven by genetic variation [4]. Typically, these populations are geographically close or share similar ecological environments.

The main drivers of natural hybridization include geographic factors and environmental changes. Firstly, geographic proximity is a key factor driving hybridization, which typically occurs when the ranges of two species overlap. For instance, in 2017, Song Feng employed SCoT molecular markers to investigate the genetic structure and interspecific gene introgression among four species and one variety of Glycyrrhiza L. populations with sympatric distributions. It was found that species with sympatric distributions, whether within the same species or between different species, exhibit closer genetic relationships. Especially in the southern and eastern regions of Xinjiang, the climate and arid environment likely played a role in the differentiation and migration of Glycyrrhiza species, creating conditions favorable for hybrid formation during this process [5]. Secondly, environmental changes, particularly species migration, are also key drivers of hybridization. And species migrating to new regions due to environmental changes may encounter local species, leading to hybridization. For instance, hybridization between the Papilio syfanius and Papilio maackii has been confirmed in the southwestern region of China [6]. In addition, ecological and behavioral differences between species, such as variations in breeding seasons and behavioral patterns, can promote hybridization under certain conditions. Some species may mate due to adaptations to similar ecological conditions, even if they differ in morphology or other physiological traits. For example, certain plant species may undergo hybridization due to overlapping flowering periods or gene flow facilitated by insect pollination.

2.2. Promotion of Genetic Diversity through Introgression

Introgression promotes gene flow by breaking down reproductive isolation between species, thereby increasing genetic diversity, which serves as a key genetic resource for species' adaptive responses to environmental fluctuations. Hybrid offspring carry genomes from different parent species, and this genetic recombination enhances the genetic diversity of populations, strengthening the species' ability to adapt to external pressures, such as pathogens or climate change [7,8].

In evolutionary processes, the genetic effects of introgression are manifested both in increased variation and in the potential formation of new species. By introducing individuals with different genetic backgrounds, hybridization helps break the existing adaptive limitations, thus providing the species with greater survival potential under new environmental conditions. hybrid offspring may carry disease-resistant or stress-tolerant genes, further boosting the population's competitive ability and adaptability.

In 2022, Zhan et al conducted a study on the introgression between common wheat (Triticum aestivum, CM104) and durum wheat (Triticum durum, 938). Employing FISH (fluorescence in situ hybridization) technology, they constructed karyotype maps for 196 individuals from pentaploid hybrids and their self-crossed progeny. The results revealed that, during the introgression process, substantial karyotype variation accumulated between common wheat and durum wheat, thereby significantly enhancing the genetic diversity of the derived progeny populations [9]. It was found that introgression enhances genetic diversity via gene flow and recombination, offering valuable insights for future plant breeding and genetic research. And this hybridization process is crucial in agricultural

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breeding, fostering the development of new crop varieties, while shedding light on the mechanisms of species evolution and the formation of genetic diversity.

Moreover, the role of introgression in agricultural breeding extends beyond the improvement of individual varieties. It impacts crop performance and long-term stability by expanding the gene pool and enhancing the crop's resistance to environmental stresses. Therefore, gradual hybridization provides essential technical support for crop genetic diversity preservation and breeding innovation, making it a key tool in sustainable agricultural development.

3. The Impact of Environmental Changes on the Introgression in Plants

3.1. The Role of Climate Change in Driving Introgression in Plants

In recent years, climate change has emerged as a global concern, with global warming presenting a major threat to all forms of life on Earth [10]. However, climate change impacts go beyond rising temperatures, including glacier melt, sea level rise, and more frequent extreme weather events, all of which affect crop growth, food supply, and other critical areas. Various changes in the ecosystem are interconnected, with any issue triggering a chain of complex reactions. Climate change directly or indirectly affects species' habitats, thus influencing gene flow. For example, rising temperatures reduce rainfall in already dry regions, leading to droughts and altering local habitats. To adapt, species may migrate to areas with more abundant water. Habitat changes and the invasion of new species create competition for native species, affecting distribution and survival [11]. In this context, the diversity of plant communities increases, and interspecies competition intensifies, providing more opportunities for introgression hybridization.

The climate change drives plant introgression by facilitating species migration and accelerating gene flow. In new habitats, gene exchange between different species accelerates, introducing new genetic variations that improve species' adaptability to changing environments. For example, under global warming, some plant species may develop new drought, disease, or cold resistance traits through hybridization, enabling better adaptation to new environments and enhancing their survival competitiveness. In some alpine plant communities, different species undergo introgression driven by climate warming. As temperatures rise, lowland plants gradually migrate to higher altitudes, increasing gene flow between these species and native ones, leading to the formation of new hybrid species. This change not only increases the genetic diversity of plant communities but also provides these plants with stronger adaptability to harsher environmental conditions. Thus, climate change plays a pivotal role in facilitating plant introgression by accelerating gene flow and genetic mixing between species. This enhances evolutionary potential and makes introgression a key strategy for plants to adapt to environmental changes and maintain survival competitiveness.

3.2. The Ecological Consequences of Biological Invasion and Introgression

Biological invasion refers to the process by which non-native species are introduced to new regions, either naturally or through human intervention, and adapt to local environments, eventually forming stable populations that pose a threat to the local ecosystem [12]. In ecosystems, species maintain complex interactions, including competition, predation, and parasitism, which are key to ecological balance. Biological invasions can disrupt this balance, particularly when invasive species compete with native species for limited resources such as food and habitat, thereby negatively impacting the growth, reproduction, and population stability of native species. In addition, invasive species may carry pathogens that trigger disease outbreaks in local species, further threatening the stability of the ecosystem. However, from another perspective, hybridization between invasive and native species may occur, potentially enhancing genetic diversity. In this context, introgression may introduce new adaptive traits, such as disease resistance or drought tolerance. This gene flow not only strengthens

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the survival competitiveness of species but also increases their potential to adapt to new ecological environments. For example, the hybridization between some invasive plants and native plants may result in offspring with stronger disease resistance, thereby improving the overall resilience of the population.

However, the ecological consequences of biological invasions are complex. Gene flow between invasive and native species can undermine the integrity of the native gene pool. While introgression increases genetic diversity, excessive gene mixing can result in the contamination of the native gene pool, reducing the stability and adaptability of its unique genotypes. Furthermore, excessive gene flow may disrupt species boundaries, potentially leading to genetic drift or even species extinction. For example, introgression between certain invasive species, such as European ryegrass, and native plants may initially increase ecosystem diversity, but in the long run, it could erode the native plants' gene pool and compromise their long-term adaptability. In agricultural and natural reserve plant communities, such gene flow may cause genetic degradation of native species, hence affecting their disease resistance and adaptability, ultimately leading to a decline in ecosystem function. Therefore, biological invasions disrupt ecological balance, and promote introgression by altering gene flow patterns, which can enhance species' adaptability, and also pollute gene pools. To address this, it is crucial to strengthen monitoring and control efforts to prevent the long-term influence of invasive species on native ecosystems, and actively examine the gene exchange between invasive and native species and its specific effects on genetic diversity, so that more scientifically informed responses can be implemented in ecological conservation efforts [13].

3.3. Potential Threats of Introgression Under Environmental Stress

Under environmental stress, introgression may pose a range of ecological threats to native species and ecosystems. As environmental changes intensify, species may adapt to new survival conditions through gene flow and hybridization with other species, forming introgression hybrid offspring. Despite the potential for gene flow to enhance a species' adaptability, it can frequently result in the contamination of the native gene pool, thereby compromising its fitness and increasing the risk of extinction. Introgression, through the introduction of foreign genes, can compromise the genetic integrity of native species, leading to the erosion of their distinctive genetic characteristics. And this genetic contamination undermines the ability of native species to adapt to environmental changes, especially when new environmental pressures, such as climate change or disease outbreaks, emerge. Excessive gene flow can cause native species to lose their environmental adaptability, potentially leading to extinction. For example, introgression may introduce foreign genes into plant species, disrupting their ecological niche and hindering their ability to survive in native conditions.

For instance, the invasive Japanese honeysuckle (Lonicera japonica) has hybridized with native plants in North America. As foreign genes gradually infiltrate, native plants may lose their disease resistance or drought tolerance, making it harder for them to maintain competitiveness in changing environments. This genetic contamination places native plants under survival pressure, leading to the degradation of ecosystem functions and affecting the entire biological community that depends on these plants. Moreover, the genetic pollution resulting from introgression goes beyond a mere loss of individual adaptability; it can trigger broader ecological chain reactions, further destabilizing the ecosystem. As foreign genes continue to infiltrate, the ecological adaptability of native plants may be markedly weakened, potentially leading to species extinction. Once native species become extinct, the species that depend on them may also face threats, ultimately leading to the collapse of ecosystem functions and potentially triggering cascading extinctions. This further exacerbates the threat to biodiversity and ecological stability [14,15].

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4. Future Prospects of Introgression

Introgression is crucial for maintaining genetic diversity, adapting to environmental changes, and driving species formation. Advances in genomics and high-throughput sequencing have deepened our understanding of its role in species evolution. However, despite existing research foundations, many uncertainties remain regarding the ecological and evolutionary consequences of introgression hybridization. Future research should leverage modern technologies to explore the specific impacts of introgression on gene flow, genetic variation, and adaptive evolution in species.

At present, a key challenge in introgression research is quantifying its impact on species gene pools and adaptability. And studies should examine how introgression promotes genetic diversity, its potential to cause genetic contamination, and its role in species' responses to environmental pressures. Especially under the climate change and ecological stress, a central question is whether introgression helps species survive and reproduce in new environments. Moreover, introgression may affect interspecies competition, ecological niche changes, and ecosystem stability. Thus, the ecological consequences of introgression should be explored, especially under habitat changes and biological invasions, examining its impact on species interactions and potential threats to ecosystem stability. Future studies should focus on gene flow patterns and ecological adaptations in species facing climate change and environmental stress. In addition, research on introgression should delve deeper into its drivers, ecological and evolutionary impacts, and delves into effective management strategies to preserve plant species' genetic diversity and ecosystem health.

5. Conclusion

This study explores the role of introgression in plant populations and its impact on genetic diversity, species adaptability, and ecosystem stability. As an important mechanism of gene flow between species, introgression introduces exogenous genes, increasing genetic variation and providing new genetic resources for species to adapt to environmental changes. The results show that introgression plays a crucial role in species' response to ecological pressures and climate change, and can provide genetic support for endangered species, reducing the risk of inbreeding depression. Therefore, introgression has a positive impact on the maintenance of biological genetic diversity and species conservation. However, it may also pose some ecological risks, particularly the potential blurring of species boundaries and genetic homogenization, which could threaten ecosystem stability. Hence, when applying introgression for biodiversity conservation, a thorough assessment of its potential negative impacts is required to ensure the long-term stability of species gene pools.

This study is limited by its reliance on a literature review, especially concerning the effects of introgression in different ecosystems. Future research should use genomic technologies to explore the molecular mechanisms of introgression and the pathways of gene flow between species. Besides, more detailed field studies are needed to investigate the role of introgression in the evolutionary process and its specific impact on species adaptability. In the future, further exploration is needed to balance the positive impact of introgression on species diversity with its potential ecological risks, and for the development of more precise species conservation strategies

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