How Does Increasing Heterozygote Advantage Influence the Rescue Probability of Diploid vs. Tetraploid Populations?

**Abstract**

In theoretical ecology, understanding the factors that enhance population survival is key. Polyploidy, a condition of having multiple sets of chromosomes, is prevalent in certain species and is thought to confer resilience to environmental challenges. This project examines whether polyploidy, specifically tetraploids, enhances population survival when heterozygote advantage (selection coefficient) is increased. How does increasing heterozygote advantage influence the survival rates of diploid vs. tetraploid populations? This question aims to explore the differential impact of selection coefficients on populations with varying ploidy levels, investigating if tetraploid populations have a survival advantage under selective pressures favouring heterozygotes.

**Introduction**

Polyploidy is the heritable condition of possessing more than two complete sets of chromosomes. Most polyploids have an even number of sets of chromosomes, with four being the most common (tetraploids). Polyploids are very common among plants and common among fish and amphibians and are usually fit and well adapted. It has been a significant driver in plant evolution, providing increased genetic variation and mutation rates, which are essential components of adaptation. Looking at the survival advantage in tetraploids, this research explores how genetic variation translates to real evolutionary success. Whether the added genetic material genuinely translates to a buffer against extinction, to help understand better natural selection mechanisms and adaptive potential.

Understanding how heterozygote advantage affects the survival rates of diploid versus tetraploid populations is a compelling question in evolutionary biology, as it delves into the complex interactions between genetics, natural selection, and population dynamics. Heterozygote advantage, often referred to as overdominance, is the scenario where heterozygous individuals exhibit a higher fitness than either homozygous type. This concept is fundamental in explaining the maintenance of genetic diversity within populations, especially for traits governed by a single locus with two alleles. Exploring this phenomenon in diploid and tetraploid populations opens avenues for understanding how genetic configurations and ploidy levels impact evolutionary trajectories, particularly under selective pressures. Given the prevalence of polyploidy in plants and its occasional occurrence in animals, examining these dynamics is crucial for a broader comprehension of adaptive mechanisms in various life forms.

One of the primary reasons this question is interesting is that polyploidy introduces unique genetic advantages and challenges. In a diploid organism, each individual possesses two sets of chromosomes, whereas tetraploids have four. This difference not only affects the gene dosage but also impacts how selection operates on alleles in the population. For instance, in a tetraploid population, the presence of two additional alleles at each locus increases the complexity of how selection acts on genetic variants. More heterozygosity can theoretically lead to greater buffering against deleterious alleles, allowing tetraploid populations to exhibit increased resilience and adaptability. Furthermore, polyploidy is a significant driver of speciation in plants, contributing to the emergence of new species with unique ecological adaptations (Otto & Whitton, 2000; Soltis & Soltis, 2000). Therefore, understanding the interplay between ploidy levels and heterozygote advantage may reveal key insights into species survival and evolutionary success.

As the heterozygote advantage or selection coefficient increases, the dynamics between diploid and tetraploid populations diverge notably. In diploid populations, the advantage conferred to heterozygotes can lead to a balanced polymorphism, where multiple alleles are stably maintained within the population. This balance occurs because heterozygous individuals have higher fitness, reducing the probability that any one allele will become fixed and dominate the gene pool. Consequently, diploid populations with a strong heterozygote advantage exhibit increased genetic diversity and resilience against selective pressures, which may improve their long-term survival rates in fluctuating environments (Crow & Kimura, 1970).

In contrast, tetraploid populations experience a more complex interaction due to the presence of four alleles at each locus. With increasing heterozygote advantage, tetraploid populations may exhibit an even greater retention of genetic diversity than diploids. For instance, the buffering effect of polyploidy can prevent the rapid loss of rare alleles, thus enabling the population to retain a broader genetic base. Additionally, tetraploids may be able to exploit environmental niches that are inaccessible to diploids due to their increased genomic flexibility and ability to harbor a wider range of allelic combinations (Comai, 2005). This flexibility could be beneficial in fluctuating or stressful environments, where a variety of genetic combinations may allow for a quicker and more adaptive response.

The implications of these dynamics are supported by research showing that polyploid plants often have broader ecological niches than their diploid counterparts, likely due to their ability to maintain higher levels of heterozygosity (Madlung, 2013). For instance, species within the genera *Trifolium* and *Arabidopsis* display substantial variation in survival and adaptation based on ploidy levels, indicating that polyploidy provides a selective advantage under certain environmental conditions (Otto & Whitton, 2000). Moreover, theoretical models have demonstrated that polyploid populations with high heterozygosity can maintain more stable population sizes, which contributes to their resilience over time (Crow & Kimura, 1970; Soltis et al., 2014). However, polyploidy is not universally beneficial; the advantage it confers may be context-dependent, varying with factors such as population size, mutation rate, and environmental stability.

Another layer to consider is that while tetraploid populations may benefit from a higher selection coefficient in terms of survival, they may also face challenges related to genome stability and reproductive compatibility. The additional sets of chromosomes in tetraploids can lead to complications during meiosis, which may result in reduced fertility or the production of aneuploid offspring (Soltis & Soltis, 2000). These factors can impose a constraint on the evolutionary potential of tetraploids, balancing out some of the benefits conferred by increased heterozygosity. Nevertheless, empirical studies have shown that, in the face of strong selection for heterozygote advantage, tetraploid populations are more likely to preserve beneficial alleles and exhibit greater adaptability over generations than diploid populations (Otto, 2007).

**Model & Methods**

This report examines the evolutionary dynamics of diploid and tetraploid populations under the influence of heterozygote advantage, focusing on how this difference impacts the survival rates of the two populations under herbicide pressure. Since tetraploidy is common in plants and some animals, this model provides valuable insights into how populations with different ploidy levels react and adapt to environmental stress. By employing a computational simulation, the study models how genetic variation and selective pressures influence population survival or extinction over successive generations, offering a framework to explore these dynamics and assess the role of genetic diversity in evolutionary resilience.

The simulation utilized two primary functions: simulate\_pop\_diploid for diploid populations and simulate\_pop\_tetraploid for tetraploid populations. These functions modeled population dynamics across generations, iteratively applying selective pressures, mutation rates, and decay rates to simulate environmental challenges such as herbicide application. The decay rate was set at 0.155 to reflect the lethality of environmental pressures, while mutation rates were kept low (0.01) to realistically simulate the rare emergence of resistance alleles.

The simulation began with an initialization phase, where populations of 250 individuals were established for both diploid and tetraploid groups. All individuals in the diploid populations carried the homozygous recessive genotype rr, while the tetraploid populations carried rrrr, representing fully susceptible individuals.

In the mutation phase, genetic variation was introduced at a mutation rate of 0.01, allowing recessive alleles (r) to mutate into dominant alleles (R). This process reflected the natural occurrence of beneficial mutations essential for population survival under selective pressures.

The next phase involved mating, where Hardy-Weinberg equilibrium principles were applied to calculate genotype frequencies for the subsequent generation. For tetraploid populations, the model accounted for their four-allele structure, which allowed for greater genetic diversity and more complex genotype combinations compared to diploids.

During the selection phase, genotype-specific fitness values were applied to simulate the impact of environmental stressors. Genotypes with higher fitness were more likely to survive, while less fit genotypes faced higher risks of extinction. To explore the effects of heterozygote advantage, a custom function, create\_sel\_coeffs, was used to generate a table of selection coefficients. This table provided a range of heterozygote advantage levels, from weak to strong, allowing the model to assess how variations in fitness impacted population survival.

The simulation looped through these phases - initialization, mutation, mating, and selection - for 100 generations. Each scenario was repeated 500 times to account for stochastic variability, ensuring that the results were statistically robust. Populations were classified as "rescued" if any individuals survived at the end of the simulation or "extinct" if no individuals remained. The survival probabilities were averaged across replicates for each heterozygote advantage level, enabling a detailed comparison of population responses under varying selective pressures.

The flow of the simulation process is summarized in the model whichh illustrates the sequential steps of initialization, mutation, mating, and selection, as well as the iterative looping through generations. The simulation’s design ensured comprehensive exploration of population dynamics and provided a robust framework for understanding how heterozygote advantage interacts with ploidy levels to influence survival outcomes.

A diagram of a process

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*Figure 1.* Model sketch summarizing the simulation process, including initialization, mutation, mating, selection, and iterative looping for 100 generations with 500 replicates per scenario.

This comprehensive methodology allowed for the rigorous analysis of population resilience and adaptability, revealing critical insights into the interplay of genetic diversity, heterozygote advantage, and ploidy levels in determining evolutionary success.

**Results**

A diagram of different types of genotype

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*Figure 2.* Fitness Landscape model for diploid and tetraploid genotypes.

The fitness landscape provides a comparative view of the genotypic fitness in diploid and tetraploid populations. In diploid populations, fitness peaked at the heterozygous genotype (Rr), while homozygous genotypes (rr and RR) exhibited lower fitness levels. These homozygous genotypes fell below the decay rate threshold, represented by a purple line in the figure, indicating that they were less likely to survive environmental challenges.

In contrast, tetraploid populations exhibited a more robust and diverse fitness distribution. Genotypes such as RRrr and RRRr displayed significantly higher fitness levels, while even the least fit genotypes (rrrr and RRRR) maintained fitness levels closer to or above the decay rate threshold. This broader fitness distribution in tetraploids illustrates their genetic buffering capacity, allowing them to retain greater genetic diversity and better withstand selective pressures. The ability of tetraploids to maintain such diversity across generations gives them a clear advantage in adapting to changing or stressful environments.

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*Figure 3*. Survival Rate Comparison Between Diploid and Tetraploid Populations Under Varying Heterozygote Advantage

The survival rate analysis highlights the contrast between diploid and tetraploid populations as heterozygote advantage increases. Both populations showed improved survival rates with increasing heterozygote advantage, but the trajectory of improvement differed between the two. Tetraploids consistently outperformed diploids, achieving higher survival rates at equivalent levels of heterozygote advantage.

At moderate levels of heterozygote advantage, tetraploid populations experienced a steep rise in survival rates, approaching near-certainty at higher advantage levels. In contrast, diploid populations showed a slower and less consistent increase, remaining vulnerable to extinction at lower levels of heterozygote advantage. These results emphasize the superior adaptability of tetraploid populations, driven by their ability to leverage genetic diversity more effectively than diploids.

The results of this study confirm the hypothesis that tetraploid populations are inherently more resilient under conditions that favor heterozygosity. The broader fitness landscape of tetraploids and their higher survival rates demonstrate their capacity to adapt more effectively to selective pressures, such as herbicide application. The ability to maintain heterozygosity and buffer against genetic drift provides tetraploids with a distinct evolutionary advantage.

These findings have broader implications for understanding how ploidy influences population resilience. Tetraploidy, prevalent in many plants and some animals, enables populations to exploit a wider range of ecological niches and withstand environmental challenges more effectively than diploids. The results provide a theoretical basis for exploring how genetic diversity and heterozygote advantage contribute to evolutionary success, particularly in stressful or fluctuating environments.

**Discussion**

The results of this study provide strong evidence supporting the hypothesis that tetraploid populations possess an inherent advantage over diploids when subjected to selective pressures favoring heterozygote advantage. The findings highlight the critical role of genetic diversity and buffering in enhancing population resilience and adaptability under environmental stressors, such as herbicide pressure.

One of the key insights from the fitness landscape analysis is the broader and more robust fitness distribution exhibited by tetraploid populations. While diploids demonstrate a fitness peak at the heterozygous genotype (Rr), their homozygous genotypes (rr and RR) fall below the decay rate, rendering them more vulnerable to extinction. In contrast, tetraploids display a wider range of viable genotypes, such as RRrr and RRRr, that maintain fitness levels above the decay rate. This genetic buffering capacity enables tetraploids to harbor greater heterozygosity, providing a critical mechanism for maintaining population stability and adapting to fluctuating environmental conditions. The retention of diverse genotypes allows tetraploids to recover more effectively from selective pressures, underscoring the evolutionary significance of ploidy level in shaping population dynamics.

The survival rate comparison further emphasizes the superior adaptability of tetraploid populations. As heterozygote advantage increases, tetraploids consistently outperform diploids across all levels of advantage. The steep rise in survival rates observed in tetraploids at moderate heterozygote advantage levels underscores their ability to leverage genetic diversity for rapid adaptation. In contrast, diploid populations show a slower and less consistent increase in survival, remaining more vulnerable to extinction even under moderate selective pressures. This disparity highlights the enhanced evolutionary potential of tetraploids in environments where heterozygosity plays a crucial role in fitness.

The broader implications of these findings are significant for understanding how ploidy influences population resilience. Tetraploidy, prevalent in plants and some animals, provides a clear adaptive advantage in environments characterized by selective pressures and stress. The ability to maintain heterozygosity and buffer against genetic drift enables tetraploid populations to exploit a wider range of ecological niches and adapt to changing environmental conditions more effectively than diploids. This advantage is particularly relevant in agriculture and conservation, where polyploid crops and species often demonstrate superior resilience to pests, pathogens, and other stressors.

Despite these advantages, it is important to recognize potential limitations associated with polyploidy. While the study focuses on the benefits of tetraploidy under heterozygote advantage, polyploidy can also introduce challenges, such as complications in meiosis, which may reduce fertility or lead to the production of aneuploid offspring. These trade-offs highlight the context-dependent nature of the evolutionary benefits of polyploidy and suggest that its advantages may vary with specific environmental and genetic factors.

The findings of this study align with theoretical and empirical evidence from prior research, which has demonstrated the evolutionary benefits of polyploidy in maintaining genetic diversity and enhancing population stability. For example, studies on polyploid plants, such as those in the genera Trifolium and Arabidopsis, have shown that higher ploidy levels are associated with broader ecological niches and increased adaptability. This study extends these insights by providing a detailed computational framework to examine how heterozygote advantage interacts with ploidy to influence survival dynamics.

**Future Directions**

While this study provides valuable insights, future research could further refine and expand upon these findings. For instance, incorporating environmental variability into the model could offer a more comprehensive understanding of how polyploid populations respond to fluctuating conditions. Additionally, exploring other ploidy levels, such as triploids or hexaploids, could provide a broader perspective on the relationship between genetic complexity and population resilience. Empirical validation of the model through experimental studies on diploid and tetraploid populations would also strengthen the theoretical framework and provide real-world applicability.

**Conclusion**

In conclusion, this study highlights the critical role of tetraploidy in enhancing population survival under selective pressures, particularly those favoring heterozygote advantage. The broader fitness landscape and superior survival rates of tetraploids demonstrate their capacity to adapt more effectively to environmental challenges, confirming their evolutionary advantage over diploids. These findings have significant implications for understanding the mechanisms underlying population resilience and provide a robust theoretical basis for future studies on polyploidy and its role in evolutionary success.

**References**

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**Author Contributions**

The project topic was developed and refined collaboratively by Rüya Eylül Arslan and Aigerim Adilbekova. Rüya Eylül Arslan was mainly responsible for the coding, and presentation design. Aigerim Adilbekova contributed by writing the report and collaborating in background research. Both authors discussed the approach together.