Evolutionary Rescue: A Hopeful Path for Species in a Changing Climate

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Abstract

Climate change poses an urgent threat to ecosystems, species, and populations through anthropogenic environmental changes like deforestation, soil and water contamination, and rising temperatures. However, species extinction is not inevitable; adaptation through a process called evolutionary rescue can enable populations to survive. Evolutionary rescue occurs when a declining population due to environmental changes adapts and recovers, typically showing a U-shaped population growth curve. This report explores the factors influencing evolutionary rescue, such as genetic variation, environmental deterioration rate, dispersal and migration patterns, and species interactions. The study reviews theoretical frameworks and recent empirical research, highlighting examples like zebrafish and Amazonian lizard species. Findings indicate that while evolutionary rescue is possible, its success is dependent on the availability of suitable habitats and high genetic diversity. Conservation strategies must prioritize habitat preservation, genetic diversity, and proactive interventions to enhance species resilience. Understanding and facilitating evolutionary rescue is crucial for reducing the impacts of climate change on biodiversity.

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Introduction

Climate change presents an alarming threat to ecosystems, species, and populations worldwide. Anthropogenic activities such as deforestation, soil and water contamination, and increasing global temperatures are accelerating the decline of many species, pushing many toward the brink of extinction (Czuppon et al. 2021). However, extinction is not an unavoidable outcome. According to theory, through a process called evolutionary rescue, species can adapt to these rapidly changing environments and avoid extinction. Evolutionary rescue occurs when a population, initially declining due to environmental changes, manages to survive and recover through genetic adaptation (Czuppon et al. 2021). This process typically features a U-shaped population growth curve, where an initial decline is followed by stabilization and recovery as the adapted genotype becomes established (Azevedo & Olofsson, 2021).

The likelihood of evolutionary rescue is influenced by several factors, including population size, genetic variation, and the rate and severity of environmental changes (Bell, 2017). Evolutionary rescue can enable populations to persist in changing environments and prevent extinction, making it highly relevant for conservation biology. Therefore, it is essential to understand the various factors that affect the probability of evolutionary rescue occurring (Ashander et al. 2019). Applying these ideas for reducing extinction risk due to human-driven global change is crucial, as understanding evolutionary rescue can lead to new effective conservation strategies that help species cope with climate change (Tomasini & Peischl, 2020).

This report investigates the theoretical background of evolutionary rescue by exploring various factors, such as genetic diversity, environmental deterioration rates, dispersal and migration patterns and species interactions. Additionally, empirical evidence is shown. By examining recent studies and case examples, such as those involving zebrafish and Amazonian lizards, this report aims to assess the effectiveness of evolutionary rescue in enabling species to adapt to the rapid environmental changes driven by climate change. Ultimately, it seeks to answer the question: How effective is evolutionary rescue in ensuring species survival amidst the accelerating impacts of climate change?

Results

Theory

Evolutionary rescue refers to the ability of populations to adapt quickly enough to avoid extinction when faced with rapid environmental changes. This process is influenced by various factors, including the rate of environmental change, genetic variation, dispersal, migration and interactions with other species (Bell, 2017). Understanding these factors is crucial for developing effective conservation strategies that can help species cope with the challenges posed by climate change and other anthropogenic influences.

<u>Rate of Environmental Deterioration</u>

The rate at which the environment changes plays a significant role in the probability of evolutionary rescue occurring. Rapid environmental changes can pose severe threats to populations, potentially leading to extinction if the species cannot adapt quickly enough. Liukkonen et al. (2021) demonstrated a trade-off between short-term performance and long-term survival, highlighting that prioritizing short-term gains can jeopardize the population's long-term viability. For example, strategies that focus on immediate survival and reproduction may jeopardize the genetic diversity needed for future adaptability. Furthermore, the timing of when mutants emergence plays a critical role in their success. Marrec & Bitbol (2020) found that mutants emerging later in degrading environments are more likely to become fixed in the population. These mutants, benefiting from increased fitness due to the changing environment and facing reduced competition with the existing population, have higher chances of success. Early-emerging mutants may not have the same advantages if the environment has not yet deteriorated enough to favour their specific adaptations.

The critical aspect here is the balance between the speed of environmental changes and the population's ability to adapt. Fast changes can outpace the evolutionary processes, leading to a high risk of extinction. In contrast, slower changes provide a window for the population to adapt through beneficial mutations. This balance is crucial for conservation strategies, which must aim to reduce rapid environmental changes to enhance the chances of evolutionary rescue.

<u>Dispersal and Migration</u>

Dispersal and migration patterns are crucial in evolutionary rescue, particularly in spatially heterogeneous environments where habitat conditions vary across different areas. In the wild, habitat deterioration does not occur simultaneously across all patches, creating a mosaic of environmental conditions. The ability of individuals to migrate between fragments and disperse within them influences the probability of evolutionary rescue. Isolated patches with low dispersal rates only affect the inhabiting population, often leading to localized extinctions. Conversely, high dispersal rates lead to more gradual habitat deterioration across the landscape, providing a better probability of adaptation. Czuppon et al. (2021) found that even a mutant slightly less fit than the wild type has an increased likelihood of adaptation with higher dispersal rates. This is because higher dispersal facilitates the spread of the mutant, particularly when it moves between habitat fragments. Increased movement between fragments reduces competition with the wild type, enhancing the mutant's chances of establishing itself. While high dispersal rates can be detrimental in stable populations due to increased competition and mixing, they become advantageous when population sizes vary, particularly by reducing competition in older, established habitats.

Dispersal and migration allow for the spread of beneficial mutations across different population patches. This movement can reduce the competition faced by new mutants and provide opportunities for these mutants to establish themselves in new environments. Conservation strategies should therefore focus on maintaining and enhancing habitat connectivity to facilitate dispersal and migration, thereby increasing the chances of evolutionary rescue.

Interactions Between Species and Within Ecosystems

No species exist in isolation; they constantly interact with other organisms, including predators, prey, competitors, and mutualists (Vanselow et al. 2021). These interactions can have both positive and negative impacts on evolutionary rescue. Environmental changes might not affect all species within an ecosystem equally. However, the decline of a population in the ecosystem can have secondary effects on other species. For instance, a population directly affected by environmental changes might survive through evolutionary rescue, but the decline could cause such disturbances that secondary species faces extinction even before the directly affected species reaches a low abundance that would typically threaten its survival (Velzen, 2023). However, interactions between species and within the ecosystem can also promote evolutionary rescue. For example, predators might prey on maladaptive individuals, because these individuals are easier to catch, thereby removing those maladaptive individuals and giving a selective advantage to those with beneficial adaptations (Vanselow et al. 2021).

The complex web of interactions within ecosystems means that changes affecting one species can ripple through and impact others. Conservation strategies must consider these interactions and aim to preserve the integrity of entire ecosystems, not just individual species. By doing so, the chances of evolutionary rescue for various species within an ecosystem can be enhanced.

Genetic Variation

Genetic variation within a population is fundamental to evolutionary rescue, as it provides the raw material for adaptation. Populations with higher genetic diversity have a broader range of traits that can be selected for in response to environmental changes. Adaptation can occur through de novo beneficial mutations or by shuffling existing genetic material within the gene pool (Liukkonen et al. 2021). Generally, beneficial mutations are already present in the existing population at very low frequencies, unless the rescue mutation has a selective disadvantage (Marrec & Bitbol, 2020). However, rescue events involving standing genetic variation are rarer compared to those from de novo mutations. Czuppon et al. (2021) research emphasizes that genetic variation within a population increases the likelihood that some individuals possess beneficial mutations, enhancing their survival and reproductive success in changing environments. This diversity allows populations to adapt more readily to new selective pressures, such as those caused by environmental degradation. In the context of their findings on dispersal and competition, genetic variation provides the raw material for selection to act upon, facilitating the spread of advantageous traits through the population.

Maintaining genetic diversity is crucial for enhancing the potential for evolutionary rescue. Conservation strategies should prioritize actions that preserve and promote genetic diversity within populations. By maintaining a diverse genetic pool, populations are better equipped to adapt to changing environments.

Empirical Studies

Multiple studies have investigated putative cases of evolutionary rescue to understand whether this process occurs under current environmental changes. Studies until 2017 are reviewed in Bell (2017); here we focus on more recent case studies.

<u>Zebrafish Study by R. Morgan (2020)</u>
Morgan et al. (2020) conducted a significant study to investigate the potential for evolutionary rescue in zebrafish (*Danio rerio*), focusing on their ability to adapt to increasing temperatures. The researchers implemented artificial selection over six generations, creating two primary selection lines: Up-selected (for increased upper thermal tolerance) and Down-selected (for decreased upper thermal tolerance). Additionally, they studied warm-acclimated fish to see if plasticity, inducible warm tolerance, had evolved. The objective was to determine the zebrafish's capacity for thermal adaptation and identify the limits of this adaptation in the face of rising global temperatures. This study is critical because understanding the thermal tolerance of species like zebrafish can provide insights into the broader impacts of climate change on aquatic ecosystems.

Morgan et al. (2020) found that upper thermal tolerance in zebrafish responded to selection as predicted, though the response was asymmetrical. The Down-selected lines exhibited a more durable response compared to the Up-selected lines, with the rate of evolution towards higher upper thermal tolerance being relatively slow at 0.04 ± 0.008 °C per generation. Furthermore, the range for plasticity due to warm acclimation decreased in the Up-selected lines, suggesting a hard limit to upper thermal tolerance. These results indicate a ceiling to how much zebrafish can adapt to higher temperatures through both genetic and phenotypic changes. Given the current rate of global temperature increase, the observed rates of adaptation and the hard limits to thermal tolerance imply that tropical fish living at the edge of their thermal limits have a low potential for evolutionary rescue.

This study emphasizes the challenges faced by species at the edge of their thermal tolerance. And as discussed in the theory that the rate at which the environment changes poses a real challenge on the probability of evolutionary rescue. The slow rate of adaptation and the hard limits to thermal tolerance suggest that these species are highly vulnerable to rapid temperature increases. Consequently, conservation strategies must focus on reducing the impacts of temperature rise and exploring other adaptive strategies to enhance the survival chances of such species.

<u>Amazonian Whiptail Lizard Study by Azevedo (2024)</u>
Azevedo et al. (2024) conducted a comprehensive study on the Amazonian whiptail lizard (*Kentropyx calcarata*), using genome-association analysis to identify candidate loci under environmental selection and modelling the distribution of individuals with genotypes adapted to different climates. The primary aim was to examine the combined impacts of deforestation and climate change on the evolutionary rescue potential of these lizards. Six genetic clusters were identified within the species, with significant hybridization observed in eastern Amazonia. The study also assessed the influence of dispersal barriers such as river drainages and dry biomes on these genetic structures. This research is crucial for understanding how habitat fragmentation and climate change jointly affect biodiversity.

The findings revealed substantial range losses due to climate change and deforestation, particularly in central Amazonia. Simulations highlighted stable habitats, new areas, and regions at risk of becoming climatically unsuitable or deforested. The results showed that many suitable habitats would become inaccessible, leading to potential extinctions. Deforestation significantly intensified the effects of climate change, further limiting the areas where evolutionary rescue might occur. Scenarios combining moderate deforestation with extreme climate change showed the most severe impacts. While some potential for evolutionary rescue exists under moderate climate scenarios, it is severely limited by ongoing deforestation. The study emphasized that reduced deforestation is crucial for preserving evolutionary rescue potential.

This research underscores the critical interplay between climate change and habitat destruction. The combined effects of deforestation and climate change significantly reduce the potential for evolutionary rescue. Deforestation leads to changes in dispersal and fragmentations of land as mentions in the theory. And leads to a decreased opportunity for evolutionary rescue to happen.

<u>Gene Diversity Study by Sofi (2021)</u>
Sofi et al. (2021) examined the genetic diversity of *Sambucus wightiana*, an endemic clonal plant species, to understand its adaptive potential and survival prospects under changing environmental conditions. The study aimed to assess genetic variability within and between populations using Simple Sequence Repeat (SSR) markers. SSR markers, also known as microsatellites, are highly polymorphic, co-dominant, and reproducible, making them ideal for evaluating genetic diversity. The researchers amplified a total of 73 alleles, with an average of 9.12 alleles per marker, revealing high levels of gene diversity. This study is essential for predicting the species' ability to adapt to new challenges and understanding the role of genetic diversity in evolutionary rescue.

The results indicated significant genetic structuring within the population, suggesting that different parts may harbour unique adaptive variants. High genetic diversity within the population provides the raw material for natural selection to act upon, enhancing the potential for evolutionary rescue. Populations with high genetic diversity are more likely to possess individuals with beneficial traits that can survive new environmental conditions. These individuals can reproduce and pass on advantageous genes, increasing overall population fitness. The findings highlighted the importance of preserving genetic diversity to enhance the adaptive potential of species in response to environmental changes.

Irshad et al. (2021) study stresses the critical role of genetic diversity in evolutionary rescue. In populations with high genetic variability, the likelihood of successful adaptation , and thereby the probability of evolutionary rescue, and survival under changing environmental conditions is significantly increased.

Collectively, these three studies highlight the varying potential for evolutionary rescue across different species and environmental contexts. Morgan et al. (2020) study on zebrafish emphasizes the slow rate of thermal adaptation and the hard limits to thermal tolerance, suggesting that tropical fish living at their thermal limits have a low potential for evolutionary rescue. This underscores the need for conservation strategies that reduce temperature rise impacts and explore alternative adaptive strategies. Azevedo et al. (2024) research on Amazonian whiptail lizards illustrates the critical interplay between climate change and habitat destruction, showing that deforestation significantly reduces the potential for evolutionary rescue. Conservation efforts must address both climate change and habitat destruction to preserve evolutionary rescue potential. Sofi et al. (2021) study on *Sambucus wightiana* highlights the importance of genetic diversity for evolutionary rescue, emphasizing the need to preserve genetic variability within populations.

These studies provide an extensive understanding of the factors influencing evolutionary rescue and the importance of integrated conservation strategies to reduce biodiversity loss under climate change. Each study stresses the need for proactive conservation efforts tailored to the specific challenges faced by different species. For zebrafish, strategies should focus on mitigating temperature increases and exploring alternative adaptive mechanisms. For Amazonian lizards, efforts should prioritize habitat preservation and reforestation to maintain the connectivity needed for evolutionary rescue. For clonal plants like *Sambucus wightiana*, preserving genetic diversity is vital to ensure adaptive potential in the face of environmental changes.

Discussion

Evolutionary rescue is the process where species adapt to rapid environmental changes induced by climate change, thereby avoiding extinction. This adaptation relies on several interconnected factors, including the rate of environmental deterioration, patterns of dispersal and migration, interactions with other species, and crucially, the level of genetic variation within populations. Understanding these dynamics is essential for predicting and effectively managing the potential for evolutionary rescue in today's rapidly changing environments.

The rate at which the environment changes is critical for the success of evolutionary rescue. Studies by Liukkonen et al. (2021) and Marrec & Bitbol (2020) emphasize that rapid environmental changes can outpace the evolutionary processes, leading to a high risk of extinction. In contrast, slower changes provide a window for populations to adapt through beneficial mutations. Moderate climate scenarios show promise for evolutionary rescue, whereas extreme scenarios, intensified by deforestation, severely limit this potential. Therefore, conservation strategies must aim to reduce rapid environmental changes to enhance the chances of evolutionary rescue.

Dispersal and migration are crucial for the spread of beneficial mutations across different population patches. Research by Czuppon et al. (2021) found that higher dispersal rates increase the likelihood of adaptation by facilitating the spread of mutants. Conservation strategies should focus on maintaining and enhancing habitat connectivity to facilitate dispersal and migration.

Species interactions within ecosystems can have both positive and negative impacts on evolutionary rescue. Studies by Vanselow et al.(2021) and Velzen (2023) highlight the complex dynamics of species interactions. Conservation strategies must consider these interactions and aim to preserve the integrity of entire ecosystems, not just individual species.

Maintaining genetic variation is crucial for enhancing the potential for evolutionary rescue. Studies by Liukkonen et al. (2021), Marrec & Bitbol (2020), and Czuppon et al.(2021) emphasize the importance of genetic diversity. High genetic diversity within populations ensures a reservoir of individuals with beneficial traits capable of thriving under changing conditions. Conservation strategies should prioritize actions that preserve and promote genetic diversity within populations

The insights from the empirical studies highlight the necessity of broad, integrative conservation strategies that address both immediate threats and long-term adaptive potential. Habitat preservation and restoration are fundamental, as demonstrated by the studies on Amazonian lizards and clonal plants. Protecting existing habitats, preventing deforestation, and reforesting degraded areas are crucial steps to maintain the spatial connectivity required for species to adapt to changing environments. Additionally, understanding and preserving genetic diversity within populations, as highlighted by Sofi's study, is essential for enabling evolutionary rescue. Genetic diversity provides the raw material for natural selection, allowing populations to adapt to new challenges and increasing their resilience to environmental changes.

In the context of climate change, conservation strategies must also consider assisted migration, where species are relocated to more suitable habitats as their current environments become inhabitable. This approach, while controversial, may be necessary for species with limited adaptive potential, like the zebrafish. Moreover, conservation efforts should incorporate climate modelling and predictive analyses to identify potential safe zones and areas at risk, enabling proactive measures to protect vulnerable species. The integration of ecological, genetic, and climate data can inform more effective and targeted conservation strategies, enhancing the chances of evolutionary rescue and long-term species survival.

The studies by Morgan et al. (2020), Azevedo et al. (2024), and Sofi et al.(2021) collectively stress the complex interplay between genetic diversity, habitat preservation, and climate change in determining the potential for evolutionary rescue. Each study provides valuable insights into the mechanisms of adaptation and the critical factors influencing species survival under changing environmental conditions. Conservation strategies must be diverse, addressing both immediate threats and long-term adaptive potential. Protecting habitats, preserving genetic diversity, and reducing climate change are essential components of effective conservation efforts. By integrating these approaches, we can improve the resilience of species and ecosystems, supporting their ability to adapt and thrive in a rapid changing environment.

Ashander et al. (2019) explores theoretical models to understand and optimize conservation management interventions that enhance the likelihood of evolutionary rescue, thus preventing extinction of endangered species under climate change scenarios. The model combines demographic and genetic dynamics to simulate population responses to environmental changes, assuming a scenario of decelerating environmental change. Initially, the change is too rapid for evolutionary rescue, but eventually slows down. Interventions include habitat restoration, which increases the long-term carrying capacity, and temporary measures like captive breeding and resource provisioning to boost population size during critical periods. The model identifies the optimal timing and intensity of these interventions, ensuring population persistence above a critical threshold while minimizing costs.

Ashander et al. (2019) study highlights the importance of early and sustained conservation intervention to prevent population extinction in the face of climate change. Initiatives like habitat restoration, assisted migration, and ongoing protection of genetic diversity are vital. These efforts necessitate significant resources and coordinated action, ensuring that populations continue to evolve even after achieving initial stability.

Evolutionary rescue presents a viable strategy for species adaptation in the face of rapid environmental changes induced by climate change. Its success, however, depends on proactive conservation actions that address multiple environmental and genetic factors. By investing in strategies that preserve genetic diversity, protect habitats, and reduce the impact of climate change, we can improve the resilience of ecosystems and species. This global approach can decrease the risks of extinction and preserve biodiversity in a rapidly changing world.

Future research should continue to explore the dynamics of evolutionary rescue, focusing on understanding the interactions between different factors and developing predictive models. Long-term monitoring and empirical studies are essential for assessing the effectiveness of conservation strategies and optimizing them based on new insights. By stimulating collaboration between scientists, policymakers, and communities, we can create a sustainable future where both biodiversity and human well-being are preserved.

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