

Evolution and Climate Change

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Abstract

Climate change is impacting all domains of life on Earth. This review explores the various ways climate change influences evolutionary processes, including phenotypic plasticity, genetic adaptation, and range shifts. Biological changes in the distribution of life forms are occurring in marine, freshwater, microorganism, and terrestrial organisms. These biological changes are a result of global warming caused by climate change. Coral reefs adapt to new environments by improving their ability to survive in a warm ocean. The coevolution of darker and pale-gray morphs is due to genetic adaptation in the environment. Both freshwater and marine organisms have been disrupted, especially in their distributions by constant climatic changes. This review concludes that climate change is equally an important crisis to humans as to evolution. Implementing conservation practices, evolutionary theory, and knowledge about climate would help safeguard biodiversity in a constantly changing world.

Keywords

Climate Change, Evolution, Phenotypic Plasticity, Genetic Adaptation, Range Shifts

1. Literature Search and Review Methodology

To assemble the evidence for this review, a systematic literature search was conducted using Google Scholar, PubMed, and Web of Science. The primary search terms included combinations of “climate change”, “evolution”, “phenotypic plasticity”, “genetic adaptation”, “range shifts”, “marine organisms”, “terrestrial organisms”, “freshwater organisms”, and “microorganisms”. Only peer-reviewed articles, and authoritative institutional reports, including UNESCO, World Meteorological Organization, were prioritized, with an emphasis on studies reporting empirical data, meta-analyses, or long-term observational records. Preference was given to research that explicitly measured evolutionary or plastic responses to documented climate variables. The review is organized conceptually: first, the

conceptual framework distinguishing phenotypic plasticity from genetic adaptation; second, evidence from marine, terrestrial, freshwater, and microbial systems; and finally, a synthesis of conservation implications and future research needs.

2. Introduction

Evolution is the genetic change in a population over generations. These changes can be caused by many factors, including mutation, genetic drift, natural selection, and non-random mating. Among these factors, only natural selection can be seen as an adaptation in situ environments. Natural selection, as proposed by Charles Darwin, is the primary mechanism by which evolution occurs [1]. The process by which organisms develop features or characteristics that enhance their survival and reproduction in a particular environment is known as evolutionary adaptation.

It is important to distinguish evolutionary adaptation from a second, non-heritable response mechanism: phenotypic plasticity. Phenotypic plasticity refers to the ability of a single genotype to produce different phenotypes when exposed to different environmental conditions, without any permanent genetic change. Whereas evolutionary adaptation alters allele frequencies across generations through natural selection, phenotypic plasticity allows an individual organism to adjust to environmental variation within its own lifetime. Both mechanisms can help populations persist under climate change, but they operate on different timescales and have different evolutionary consequences. This review examines evidence for both responses while maintaining a clear conceptual separation between plastic adjustments and true genetic adaptation. In most species, evolutionary changes happen at a faster rate and help them to counter stressful conditions [2]. Native populations are reacting to constant environmental changes by moving their range.

Climate change mostly exerts strong selection pressures on characteristics or features critical for fitness. Again, changes in natural or human-caused factors, as well as biotic and abiotic factors, whether driven by shifting temperatures, altered precipitation patterns, or habitat fragmentation, can increase directional selection [3] [4]. Climate change does not always impose directional selection pressure. As birds expand into new habitats, stabilizing selection may shape their breeding phenology, favoring individuals that reproduce within an optimal environmental condition [5]. When confronted with new stresses, like those caused by continuing climate change, populations mostly respond in three ways. First, they can escape by moving to more appropriate surroundings. Second, they can also adjust to new environments through phenotypic plasticity without changing genetic makeup. Finally, the population can cope with altered conditions through genetic adaptation, heritable changes in allele frequencies across generations driven by natural selection, through the process of evolution [6]. While adaptations and phenotypic plasticity can prevent local extinction, evading would lead to extirpation (local extinction of a species in a specific geographic area, distinct from global

extinction) [7]. These processes are essential for keystone species encountering threats coming from climate change [8]. The importance of these three responses as survival strategies differs according to the time taken into consideration, the life history of the organism, and the capacity of species to disperse naturally or artificially.

Range shifts, changes in the geographic distribution of a species beyond its historically documented boundaries, represent a critical mechanism by which species respond to climate change. Range shifts are mostly driven by anthropogenic factors, including climate change [9]. A growing body of empirical evidence convincingly demonstrates these distributional responses to warming temperatures and altered precipitation patterns, with species moving poleward at a median rate of 16.9 km per decade and to higher elevations at 11.0 m per decade [10]. While phenotypic plasticity, the ability of a single genotype to express different phenotypes under varying environmental conditions, does not provide a permanent solution for populations facing sustained environmental change, it nevertheless offers an essential, short-term adaptive mechanism that allows species to persist while longer-term evolutionary responses or range shifts occur [11] [12].

In recent times, scientists have gathered enough knowledge and information through investigation and exploration about climate change [3] [13]. Global surface temperatures have increased rapidly, and these changes are enough to alter the ecology and evolution of life on Earth [14]. Climatic changes driven by astronomical cycles have repeatedly triggered shifts in biodiversity, resulting in both rapid speciation events and increased extinction rates. While some species failed to adapt and perished, others evolved quickly in response to novel environmental conditions.

This review explores how organisms are evolving in response to climate change, examining the relationship between phenotypic plasticity, genetic adaptation, and range shifts. By adding recent research, this review aims to simplify the mechanisms driving these responses and the implications for biodiversity in a constantly changing world.

3. Phenotypic Plasticity and Genetic Adaptation in Response to Climate Change

It is widely known that recent climatic changes have had huge effects on the behavior and distribution of various plant [15] and animal [16] species. However, the mechanisms by which these effects arise, and their implications for population persistence, remain poorly understood. Microevolutionary responses to phenotypic plasticity and natural selection are the major ways that can describe inhabitants' responses to climate change. Genetic adaptation is considered microevolutionary response because it occurs over a short period within a species. There is a lot of evidence barking the argument that climate-driven changes in population behavior are genetically based [17]. Few researchers also believe that it is caused by individual plasticity [18] [19]. The primary protection against changing cli-

mates is phenotypic plasticity, which is the capacity of an individual to change its characteristics in countercharge to environmental changes without enduring genetic alteration or composition.

Phenology, the timing of seasonal biological events, is known to be the most well-documented responses to climate change. This is not surprising as phenological changes are mostly connected to seasons and agriculture. Increasing temperatures and patterns have caused statistically significant evidence of advancement and disruption in life cycle processes across species. According to Franks *et al.*, (2017), flowering times in plant species illustrate trends of earlier flowering with climate change, a behavioral shift that is mostly plastic in nature [20].

Although phenotypic plasticity provides a temporary defense against environmental change, its boundaries are mostly tested under constant climatic change [21]. For instance, some amphibians, including the *Lithobates sylvaticus* (wood frog), can modify their freezing tolerance in response to colder seasons [22]. Again, prolonged warming seasons could go beyond their adaptive capacity [23]. Coral reefs are a perfect example of phenotypic plasticity. Phenotypic plasticity allows corals to change or adapt to new environments by improving their ability to survive in a warm ocean [24]. Light, an abiotic factor, is key for determining coral distribution. They establish a symbiotic relationship with algae and this relationship depends on light intensity in the ocean. Coral reefs show plasticity through symbiont shuffling. This is when coral reefs host several types of algae to manage with rising sea temperatures [24]. The widespread coral bleaching events when temperatures exceed tolerable thresholds show some limitation of phenotypic plasticity [25].

On the other hand, genetic adaptation, the process by which allele frequencies within a population vary across generations, produces heritable features that improve reproduction and survival of individuals [26].

Genetic adaptation can be observed in the color morphs of *Strix aluco* (tawny owls) [27]. In colder, snow-prone environments, pale-gray morphs are more common because their lighter coloration provides better camouflage against snow, reducing predation risk. Conversely, darker morphs are more common in warmer, less snowy environments where darker coloration offers superior camouflage against bare ground and tree bark [27]. Climate mediates this selection pressure directly: as winter snow cover becomes more or less persistent, the survival advantage shifts from one morph to the other. Studies have confirmed that these color differences are heritable, representing a genuine case of genetic adaptation to local climatic conditions [27].

Similarly, the *Fundulus heteroclitus* (Atlantic killifish) has quickly evolved to survive in high levels of environmental pollution [28]. This demonstrates the potential for rapid genetic adaptation in response to extreme anthropogenic stressors. In addition, studies on *Drosophila melanogaster* (fruit flies) have shown that populations can evolve rapidly in response to temperature stress, increasing heat tolerance over many generations [29]. These illustrations highlight how natural

selection can influence micro-evolutionary (genetic alterations) in response to environmental stressors.

Genetic adaptability and plasticity are the two main ways organisms respond to changing environmental conditions. Even though they interact in a different way, plasticity can delay population for genetic adaptation to take place. But when climatic changes overtake both processes, extinction risks increase. The evolutionary processes of climate change responses are further confounded by the probability of evolution in plasticity genes, the genetic foundations of plasticity itself. Anticipating how resistant species will be to constant global warming requires an understanding of how these systems work. While the relationship between phenotypic plasticity and genetic adaptation provides a background for understanding evolutionary responses to climate change, these mechanisms show differently across ecosystems. Terrestrial, freshwater, and marine environments each present exceptional challenges and opportunities for species facing climatic changes.

4. Marine Organisms

On Earth, the oceans are acknowledged as the largest habitat. The physiology and distribution of animals are already being impacted by ocean climate change. Warmer temperatures, acidification and deoxygenation are some of the consequences of climate change that impact marine organisms [30].

The change in temperature from excessive heat warms the ocean and leads to profound effects like sea-level rise and marine heatwaves [31]. These profound effects ultimately cause an impact on marine biodiversity. Recent records from the World Meteorological Organization show that the worldwide mean sea rise has reached a new range from 2013 to 2016 [32].

Marine heatwaves, the prolonged duration of abnormal high sea surface temperature, have come out as a major ecological disturbance under climate change. Marine heatwaves have increased in duration, frequency and intensity [33] with effects on marine biodiversity and ecosystem function. About sixty percent of the world's ocean surface experienced marine heatwaves [34]. Heatwaves trigger mass coral bleaching processes, leading to deterioration of reef ecosystem. Under high-emissions scenarios, some models project that by 2100, the majority of the world's coral reefs could experience annual severe bleaching events, potentially leading to widespread reef degradation [35].

Mass mortality results from coral bleaching. Bleaching is brought by the removal of symbiotic algae by the coral reefs under stress. Nevertheless, some corals demonstrate resilience forming connections with algae that can withstand higher temperatures or stress. Despite these adaptive mechanisms, the fast rate of climate change mostly exceeds the capacity of coral to adapt, and this results in widespread reef degradation. Under a high-emissions scenario, some modeling studies cited by UNESCO project that approximately 50% of marine species could face elevated extinction risk by 2100, though these outcomes depend strongly on future emissions trajectories and species-specific adaptive capacities [36].

Fish is an important composition in aquatic ecosystem, processes and food chain. The fish populations are responding to climate change through biological adaptation and shifts in distribution. The fish populations are shifting their ranges to deeper waters to escape warming surface temperatures. Regions such as the North Atlantic and North Pacific are experiencing an increase in the range of some fish species. Their high susceptibility to climate change caused an unreliable future for fish. Many fish are evolving into smaller body sizes and earlier maturation due to warmer waters [37]. These changes affect marine food webs, as predator-prey interaction and resource availability are interrupted.

The increased absorption of carbon dioxide from the atmosphere by the ocean is termed ocean acidification. Ocean acidification is a threat to marine organisms and also changes the pH of the ocean. It is common with mollusks and some planktonic species. Likewise, ocean acidification damages the ability of coral reefs to calcify further increasing their exposure to other stressors.

Deoxygenation is also another serious consequence of climate change. Warmer waters hold less oxygen compared to cold waters. The oxygen molecular concentration of the ocean has been lowered by about two percent since the beginning of the twentieth century [38]. Similarly to marine species extinction, ocean oxygen concentration is expected to decline on average by four percent by the year 2100. Current stratification caused by surface warming prevents mixing, limiting oxygen molecules movement from surface waters to deeper layers. This creates dead zones where there is no oxygen to support most marine life. Deoxygenation leads to disruption in ecosystem services by interrupting ocean food chain supply.

Overall, some broader implications of climate change in the marine environment include disruption of marine food webs due to shifts in species distributions, loss of biodiversity in coral reef ecosystems, and finally economic impacts on fisheries and coastal communities reliant on marine resources. Conservation practices should prioritize enhancing monitoring, especially on marine heatwaves forecasting and reducing non-climate stressors including overfishing and pollution.

5. Terrestrial Organisms

Terrestrial organisms are made up of a vast biodiversity spectrum, each having different niche stratification requirement and life history features or characteristics. Disturbances, starting with altered fire regimes and compounded by climate change, have interrupted the biological relationships among communities. Climate change also affects the functions of the existing ecosystem. Terrestrial species are already experiencing habitat loss and fragmentation [39]. Changes in temperature would further alter conditions of suitable habitats.

Organisms may counter to habitat changes by migrating into more desirable places or else adapting or by going extinct. Many terrestrial organisms show range shifts, moving to higher elevations for suitable conditions. Alpine plants are shifting upward every decade while European butterflies are also shifting their ranges from northward over the same period [40].

Activities such as senescence, mating and breeding show sensitive responses to climate change [41]. Some mammals including *Tamiasciurus hudsonicus* (American red squirrel), have increased breeding times in relation to earlier springs. Also, some plants change their flowering periods to reflect shifting seasons. The *Vulpes vulpes* (red fox) shows how climate change can drive range shifts and competitive interactions in terrestrial ecosystems. Historically, the red foxes are restricted to lower areas and temperate climates [42]. They are currently migrating upwards into Arctic areas or regions.

To conserve biodiversity, evolutionary principles with adaptive management strategies must be implemented. Conservation strategies including assisted migration and genetic rescue, even though controversial, are vital in enhancing genetic diversity and facilitating range shifts. This would help species survive in a rapidly changing environment.

6. Freshwater Organisms

Freshwater encompassing both groundwater and surface waters is vital to life on Earth. Organisms in freshwater are more susceptible to climate change than any other organisms. This is because freshwater temperatures are climate dependent and many organisms within this ecosystem have restricted capabilities to migrate as the environment modifies. Also, they are already exposed to anthropogenic stressors.

Freshwater fish are directly influenced by water temperature, and studies indicate that high-latitude freshwater fish in the Northern Hemisphere are projected to face the greatest reductions in warming tolerance, making them particularly vulnerable to climate change [43]. By contrast, marine fish in the tropics are at greater risk due to their higher intrinsic physiological sensitivity, as they already live near their upper thermal limits [43].

The spread of invasive species in freshwater ecosystem is expected to increase. For example, invasive species such as the *Cyprinella lutrensis* (red shiner), which are more salinity tolerant than native freshwater fish, are being favored due to increased salinity from low precipitation and higher evaporation rates [44].

The building of reservoirs, mostly motivated by water storage needs under climate change, can boost the increase of invasive species by removing natural boundaries and creating new habitats. Changes in streamflow routines, especially in floods, may remove natural filters that block the introduction of non-native species. These interactions highlight the complex ways in which climate change and non-native organisms mutually threaten freshwater biodiversity. Organism in freshwater species are experiencing evolutionary changes with many unable to adapt quickly enough to survive climate change. Proactive conservation including habitat protection, policy innovation and assisted gene flow is critical to preserve freshwater biodiversity.

7. Microorganisms

Climate change is the greatest health risk facing humanity according to the World

Health Organization. As the most abundant organisms on Earth, microbes are not immune to these changes. They are currently adapting to a changing climate, causing implications for humanity. Generally, microorganisms reaction to climate change rely on microbial history [45]. The consequences of climate change on microbes in both terrestrial and aquatic ecosystems are complicated. Recent articles show that fluctuations in temperatures have an influence on microbial diversity at geographical range, distribution and phenology [45].

Microorganisms such as bacteria tend to decrease in abundance with increasing latitude as temperature declines [46]. Changes in temperature can influence the variety of microorganisms through numerous processes [47]. There is also an increase in evolutionary processes such as mutation, speciation and interaction from increased temperatures [48] [49]. However, increased temperature can also selectively favor more adapted microorganisms while limiting the stochastic drift and distribution of species [50].

8. Concluding Thoughts on Evolution and Climate Change

The increasing effects of climate change are testing the thresholds of evolutionary change across all domains of life. This review has shown that ecological constraints, genetic adaptation, and phenotypic plasticity shape how terrestrial, freshwater, marine, and microbial organisms respond to a warming world. Importantly, climate change is not exclusively a force of decline. Throughout Earth's history, shifting climates have driven speciation, adaptive radiations, and the spread of species into new regions. Even today, some organisms benefit from warmer temperatures, longer growing seasons for certain plants, and increased evolutionary rates in microbes may accelerate adaptation.

However, the critical issue is not climate change itself, but its unprecedented rate. Past climatic transitions often occurred over millennia, giving populations time to migrate, adapt, or evolve. Current anthropogenic warming is happening over decades to centuries, a pace that outstrips the adaptive capacity of many long-lived, specialized, or geographically restricted species. While some organisms show rapid genetic adaptation, many others cannot keep up. The result is a net loss of biodiversity, ecosystem function, and resilience, even if a minority of species thrive.

The planet has experienced climate change throughout its history and the organisms adapt. Acknowledging past adaptations does not negate the severity of current threats but it rather underscores that evolution is a race against time. Without proactive conservation, including assisted migration, genetic rescue, and emission reductions, many lineages will go extinct before they can adapt.

The adverse outcome of biodiversity relies on our ability to connect evolutionary theory with feasible and ready policy. Climate change is a double-edged sword: it drives innovation in some branches of the tree of life while severing others. Our task is to tilt the balance toward persistence by buying time for evolution through rapid mitigation and intelligent management.

9. Study Limitations and Confounding Stressors

This review has focused primarily on the direct evolutionary and plastic responses of organisms to climate change. However, it is important to acknowledge that in natural systems, climate change does not act in isolation. Species are simultaneously exposed to multiple anthropogenic stressors, including habitat loss and fragmentation, chemical pollution, invasive species, and overexploitation. These factors can interact with climate stressors in complex ways, weakening physiological resilience, or altering species interactions. Disentangling the specific effects of climate change from these co-occurring stressors remains a significant challenge for conservation biology. Future research should prioritize multi-stressor studies that better reflect real-world conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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