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CLIMATE CHANGE AND ITS IMPACT ON GENETIC DIVERSITY, MOLECULAR ADAPTATION, AND ECOSYSTEM RESILIENCE: A COMPREHENSIVE REVIEW

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ABSTRACT:
Climate change is increasingly altering biological systems across genetic, population, and ecosystem levels, with important consequences for biodiversity persistence and adaptive capacity. This comprehensive review examines how climate-related environmental stressors influence genetic diversity, molecular adaptation, and ecosystem resilience across terrestrial, freshwater, and marine environments. Genetic diversity provides the heritable variation required for populations to respond to changing environmental conditions, whereas genetic erosion, population bottlenecks, and habitat fragmentation can restrict adaptive potential. Climate-driven selection can alter allele frequencies and promote adaptive responses, while gene flow and population connectivity contribute to the maintenance of evolutionary potential. Advances in genomics, transcriptomics, epigenetics, and multi-omics have improved understanding of adaptive genetic variation, gene-expression responses, phenotypic plasticity, and molecular mechanisms associated with environmental stress. Ecosystem resilience is further shaped by functional diversity, species interactions, genetic variation, and landscape connectivity. Climate-smart conservation, assisted gene flow, ecological restoration, and genomics-informed management provide important approaches for maintaining adaptive capacity and biodiversity. Greater integration of molecular, ecological, and environmental information with long-term monitoring is needed to strengthen conservation planning and ecosystem resilience under accelerating climate change.

KEYWORDS: Climate change; Conservation genomics; Ecosystem resilience; Genetic diversity; Molecular adaptation

1. INTRODUCTION

Climate change has become one of the largest environmental issues facing the world and has a significant impact on biodiversity, both at the genetic, species, and ecosystem level. Habitats and ecological processes are changing in both terrestrial, freshwater and marine environments in response to rising temperatures, changing precipitation regimes, ocean acidification, sea level rise, and more frequent extreme weather events. These climate shifts have contributed to species distributions, reproductive and migration cycles, and local extinctions of numerous taxa. Biodiversity loss is no longer just attributed to habitat loss or pollution but is now associated with climate-related environmental stressors impacting the whole world and threatening ecological stability. Climate change is also found to exacerbate risks to ecosystem services under other anthropogenic stressors and to undermine the long-term sustainability of ecosystems as shown by recent global assessments (Brondízio et al., 2019). Vulnerability assessments of species also show that climate-sensitive species can have limited adaptive capacity if environmental changes do not occur within their physiological and ecological limits of tolerance, further emphasising the need to incorporate climate adaptation into the process of conservation planning for biodiversity (Foden et al., 2019).

In addition to its ecological effects, climate change is a strong evolutionary driver as it changes selective pressures affecting genetic composition within populations. If the environment changes rapidly, organisms must evolve or change their location to more preferred habitats or else their population will suffer. Over comparatively brief evolutionary time, genetic variants that increase resistance to higher temperatures, drought, salinity or shifts in resource availability increasingly favored by natural selection and thus affect the frequencies of different alleles. Due to the recent progress of population genomics, some taxa have been found to have detectable genomic signatures of adaptive evolution in response to changing climatic conditions (Bay et al., 2018). More recently, the use of modern analytical methods, such as genotype environment association analyses, has enhanced the power to identify adaptive loci associated with environmental gradients and helped to elucidate evolutionary responses to climate stress (Forester et al., 2018). The results highlight the evolutionary nature of climate change as a process that constantly alters the genetic structure of natural populations, as well as the ecological aspect of the disturbance.

Populations have adaptive potential only because of genetic diversity, which provides them with heritable variation to adapt to environmental change. Genetically fewer variable populations tend to be more susceptible to climatic changes, disease outbreaks, habitat alteration, inbreeding, reduced fitness, and extinction, while more genetically variable populations are more resilient to climatic disturbances, disease outbreaks and habitat alteration. Anthropogenic climate change is observed to be affecting many species and their ability to adapt to future changes, through a reduction in their genetic diversity (Exposito-Alonso et al., 2022). Conservation strategies are now shifting to the importance of maintaining intraspecific genetic variation as an integral part of the functioning of the ecosystem and continuing ecosystem services to people (Des Roches et al., 2021). Molecular adaptation provides additional sources of variation to genetic variation, including adaptive gene expression, genomic variation and physiological plasticity, which allow organisms to cope with variable environments. In this context, the incorporation of evolutionary thinking into molecular genetics has been gaining relevance for the development of successful conservation actions in future climate scenarios (Gaitán-Espitia & Hobday, 2021; Miller et al., 2026).

The rapid progress in genomics, molecular ecology and conservation biology have significantly advanced the understanding of the effects of climate change on biological systems, ranging from the gene to the ecosystem level. However, knowledge is dispersed in different fields and it is difficult to achieve an integrated vision on the genetic diversity, molecular adaptation and ecosystem resilience relations. This study brings together recent scientific evidence on the mechanism by which climate change influences genetic variation, adaptive molecular responses and ecological resilience in several ecosystems. Special focus is given to how genomic technologies, evolutionary processes and conservation genetics contribute to the understanding of adaptation of species and to the conservation of biodiversity in the context of accelerating climate change. Additionally, the study addresses current research gaps and future directions for maintaining biodiversity in a shifting global climate, and emerging strategies that leverage genetic information to build ecosystem resilience and inform conservation planning for climate change.

2. METHODOLOGY

Extensive literature searches were conducted to identify relevant literature published between 2016 and 2026. Educational and scientific value, methodological soundness, timeliness and relevance to understanding links between climate change, genetic diversity, adaptive molecular responses and ecosystem resilience in terrestrial, freshwater and marine ecosystems were all considered in evaluating the selected publications. Relevant publications from the literature were assembled according to the themes of the work to compile existing evidence on evolutionary processes, molecular mechanisms, ecological implications, conservation approaches and new research priorities. This allows a comprehensive and integrated review of recent advances in science and to identify knowledge gaps and future directions for research in the field.

3. Climate Change as a Driver of Evolutionary and Ecological Change

3.1 Major Climate Stressors Affecting Biological Systems

Multiple environmental stressors have been increased by climate change, which together affect the structure and functioning of biological systems. The increase in global temperatures, changes to precipitation patterns, extended droughts, warming and acidification of the oceans, habitat loss, and an increase in extreme climatic events are all impacting ecological processes in terrestrial, freshwater and marine ecosystems. They shift species distributions, change phenological events, make habitats less suitable and impact reproductive success, which impacts ecosystem productivity and stability. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the rate and scale at which climatic conditions are changing unprecedented in recent history and has impacts on biodiversity and ecosystem functioning (Legg, 2021). Regional evaluations also show that climate change has emerged as one of the most important challenges in conservation of biodiversity along with land-use change, pollution and alien species (Yousefi et al., 2019). All these pressures threaten the adaptive capacity of organisms and can accelerate the possibility of irreversible ecological change without the effective implementation of mitigation and conservation. The major climate-related stressors and their cascading effects on organisms, populations and ecosystems are shown in Figure 1. The framework emphasizes the connection between evolutionary and ecological processes that are triggered by environmental changes and affect biodiversity.

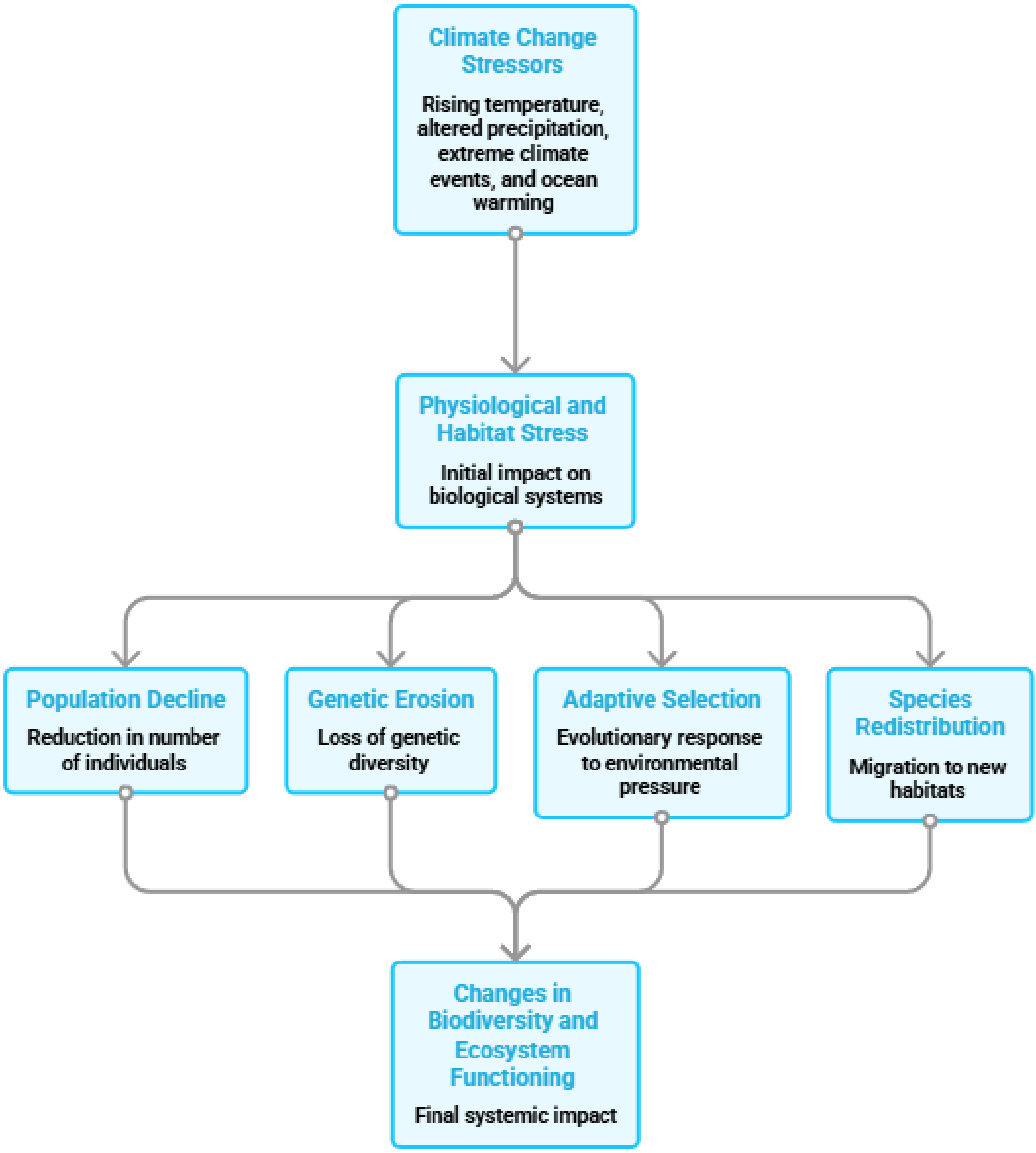

Figure 1. Climate Change Stressors and Their Cascading Effects on Biological Systems

3.2 Evolutionary Responses to Rapid Environmental Change

Natural populations are subjected to strong selection pressures because of environmental change. Species can react in various ways genetic adaptation, phenotypic plasticity, change in life history traits or spread of range to suitable climates. Adaptive genetic variation allows populations to persist in the face of a changing environment by making advantageous alleles more common within the population, which increases the likelihood the population will persist in the future. The addition of adaptive genetic variation to climate vulnerability assessments has been demonstrated to significantly enhance predictions of species persistence and reduce projected range contractions from those based on ecological variables only (Razgour et al., 2019). However, many organisms can adapt to climate change at a slow rate of change, whereas the rate of climate change at present is unprecedented. This means that species with low dispersal capacity, long generation times and low genetic diversity are sensitive to population declines. Abiotic and biotic factors, in other words, both play a role in the success of a species adaptation and distributional shift to future climate scenarios, according to recent studies on climate-driven range shifts (Osmolovsky, 2025). The mechanisms of evolution are therefore fundamental to understand biological reactions and to establishing appropriate conservation programs.

3.3 Species Vulnerability Across Different Ecosystems

Vulnerability to climate change is not uniform across all ecosystems, but depends on a variety of factors such as climate, ecological interactions, and evolutionary history. Climate warming drives cold-adapted species to higher elevations, increasing thermal stress and changing hydrological patterns and water quality in freshwater ecosystems, with rapid loss of habitat in these areas. The changes in species composition and functioning of ecosystems are extensive because of warming, acidification, and deoxygenation of the oceans, especially in marine ecosystems. In every ecosystem, loss of genetic diversity is a loss of future adaptive potential that is necessary for long-term survival. Loss of genetic variation in wild populations since the industrial revolution has been measured, and it is estimated that a significant proportion of genetic variation has already been lost, compromising their ability to withstand future environmental change (Díaz et al., 2019; Leigh et al., 2019). Likewise, there is a lack of proper inclusion of the protection of genetic diversity in international conservation frameworks, although it is an essential component of the ability of ecosystems to recover from disturbances (Laikre et al., 2020). The integration of genetic conservation with principles of climate adaptation is becoming more common in ecosystem-specific restoration strategies to help maintain the persistence of vulnerable species in the face of climate change and improve ecological recovery under climate change (Keller et al., 2026). In addition, there are broad syntheses of anthropogenic impacts that suggest that climate change remains a synergy with other anthropogenic pressures, leading to widespread biodiversity losses across taxonomic groups, including birds and other highly sensitive vertebrate species (Vidić et al., 2026).

4. Climate Change and Genetic Diversity

4.1 Importance of Genetic Diversity in Population Persistence

Genetic diversity is the most basic component of population persistence, as it is needed to enable adaptability to environmental variation and future climate challenges. A population with a high amount of genetic variation has a wider range of adaptive characteristics which would make it better able to survive, reproduce and adapt to the environment as it changes. Genetically rich populations have a higher evolutionary potential, and can be more resilient to environmental changes, disease attacks and extinction. Conservation of genetic diversity is paramount to preserve biodiversity and ecosystem security in the context of increasing climate change (Shaw et al., 2025). In addition, recent developments in conservation genomics have revolutionized the management of biodiversity by providing the ability to precisely identify adaptive genetic variation, population structure, and evolutionary potential, which can be used to inform evidence-driven conservation planning and action at the level of various taxa (Supple & Shapiro, 2018). As a result, maintaining genetic diversity is now a key goal of global conservation efforts focused on climate change.

4.2 Genetic Erosion and Population Bottlenecks

Genetic erosion resulting from climate change can be caused directly by habitat fragmentation, local extinctions and a reduction in population size. Demographic bottlenecks can follow extreme climatic events, environmental stress, habitat degradation, and decrease effective population size which leads to a more rapid loss of rare alleles by genetic drift. These decreases in genetic diversity decrease adaptability and reduce the capacity of populations to react to future environmental changes. In the past, adaptive responses to natural selection processes are likely to have occurred, but the unprecedented anthropogenic climate change, in most cases, is exceeding the rate of evolutionary adaptation and may enhance the risk of extinction for vulnerable species (Gienapp & Merilä, 2018). Therefore, to stop the further loss of genetic diversity, long-term genetic monitoring must be combined with conservation measures that ensure well-connected, large populations with sufficient evolutionary capacity. Table 1 summarises the main climatic drivers that cause genetic erosion and loss of adaptive capacity among biological systems.

Table 1. Major Climate Change Drivers Affecting Genetic Diversity and Population Persistence

Climate Driver	Genetic Consequence	Ecological Impact	Representative Examples	Reference
Rising temperature	Loss of adaptive alleles	Population decline	Alpine plants	(Exposito-Alonso et al., 2022)
Habitat fragmentation	Reduced gene flow	Population isolation	Forest mammals	(Leigh et al., 2019)
Extreme climatic events	Genetic bottlenecks	Reduced resilience	Amphibians	(Shaw et al., 2026)
Ocean warming	Selection pressure	Coral bleaching	Coral reefs	(Bernatchez et al., 2024)
Altered precipitation	Reduced effective population size	Local extinction risk	Freshwater fishes	(Razgour et al., 2019)

4.3 Gene Flow, Migration, and Population Connectivity

Gene flow and population connectivity are essential to ensure genetic diversity in the face of climate change. Migration benefits by allowing adaptive alleles to be shared among populations, mitigates inbreeding effects, and increases genetic variation across landscapes, which increases evolutionary resilience. But the current trend of habitat fragmentation and anthropogenic barriers to dispersal is increasingly affecting the natural movement of organisms and reduce opportunities for adaptive gene flow. The incorporation of genomic data into climate adaptation studies has significantly increased the accuracy of the predictions of species response by identifying adaptive genetic variants linked to environmental gradients and future climate conditions (Waldvogel et al., 2020). A more holistic view further underscores the need to appreciate how climate-induced ecological change, species dispersal, and landscape connectivity can work together to ensure functional ecosystems over time to enable the successful conservation of the landscape (Williams et al., 2021). To ensure long-term adaptation to climate change, it is therefore important to maintain ecological corridors and genetically connected populations.

4.4 Genomic Evidence of Climate-Induced Genetic Change

With recent progress in the genomics field, the understanding of the response of organisms to environmental changes initiated by the climate has been revolutionized. The high throughput sequencing, population genomics, transcriptomics, and other omics technologies allow researchers to characterize adaptive loci, to look for signatures of natural selection and to track evolutionary responses with unprecedented resolution. These have proven useful to estimate adaptive capacity, detect climate-sensitive groups, and guide conservation strategies in the context of a rapidly changing climate (Bernatchez et al., 2024). Ecological evidence from a variety of ecosystems now shows that genetic changes are underway in many plant and animal species, such as those important for pollination, which are undergoing large losses in species richness and distribution due to climate stress (Zattara & Aizen, 2021). Policy syntheses that have been recently undertaken also highlight the need for coordinated conservation activities at local, habitat level, and international biodiversity governance, level to prevent the loss of genetic diversity (Shaw et al., 2026). In addition, new multi-omics technologies have shed light on the intricate connections between the molecular regulation of genome, responses of physiology and ecosystem resilience, especially in aquatic systems, where the effects of climate change become more pronounced (Thangaraj & Sun, 2026). These are genomic advances that give us a strong scientific basis for creating conservation strategies that are informed by climate change and that aim to sustain biodiversity and increase ecosystem resilience to climate change.

5. Molecular Mechanisms of Climate Adaptation

5.1 Natural Selection and Adaptive Evolution

The main evolutionary mechanism that enables populations to adapt to the changing climatic conditions is natural selection. Individuals with the favorable variants have greater fitness and success in reproducing and, therefore, the frequency of the adaptive alleles becomes more prevalent in the population with time as environmental pressures build up. Through this process, species become accustomed to heat stress, drought, changes in precipitation, salinity, etc. and become tolerant. Adaptive evolution, however, will be effective only when there is adequate genetic variation and when environmental change is relatively rapid. In forest systems, for example, long-lived trees need to retain a lot of standing genetic variation to ensure their resilience in the face of fast-changing climates. There is currently evidence that many forest tree populations have significant adaptive capacity, but with ongoing environmental change, some of this adaptive capacity may be exceeded, unless there are conservation measures in place (Aitken & Bemmels, 2016; Kremer et al., 2024). In the genomic era, therefore, conserving evolutionarily significant units and maintaining genetic diversity are key to ensuring long term adaptive evolution and avoiding biodiversity loss (Coates et al., 2018).

5.2 Gene Expression Responses to Climate Stress

Under environmental stress, as caused by climate-related stressors, a series of complex molecular processes trigger responses that control cellular metabolism, physiology and tolerance to stress. Changes in gene expression provide organisms with a way to quickly modify biochemical pathways associated with antioxidant defense, protein stability, osmotic regulation, immune responses and energy metabolism. Such transcriptional alterations are frequently induced before permanent genetic change and are one way that organisms respond immediately to varying environmental conditions. El Niño events, warmer water and changes in hydrological flows are having a significant effect on the molecular reactions of freshwater life in aquatic ecosystems, which has implications for biodiversity and impacts on ecosystem function (Tonkin et al., 2026). In coral reefs, host-microbiome interactions play a significant role in the thermal tolerance and resilience of whole ecosystems in the face of climate stress, with similar molecular changes observed in the hosts (Bourne et al., 2016). These results illustrate the importance of a dynamic system in the regulation of gene expression that underlies short-term physiological adaptation and ecological persistence.

5.3 Epigenetic Regulation and Phenotypic Plasticity

Epigenetic mechanisms are another level of adaptation as they adjust the activity of the genes without changing the DNA sequence. DNA methylation, histone modifications, and non-coding RNA regulation are processes that allow organisms to alter gene expression based on environmental conditions and provide a mechanism for phenotypic plasticity to increase the chances for survival in fluctuating environments. Such reversible molecular changes enable very rapid acclimation response in response to a wide range of environmental gradients, and in some instances may play a role in transgenerational inheritance of adaptation. Genetic and epigenetic regulation of neural plasticity, physiological resilience, and adaptive responses to chronic climate stressors now play a growing role in understanding how organisms adapt to climate change in the future, as highlighted by recent research (Uddin et al., 2026). The inclusion of epigenetic studies in the field of climate biology thus provides useful clues to mechanisms in addition to evolutionary adaptation. To explore the linkages between gene expression, epigenetic regulation, phenotypic plasticity, and adaptive evolution, the main molecular pathways that contribute to climate adaptation are shown in Figure 2.

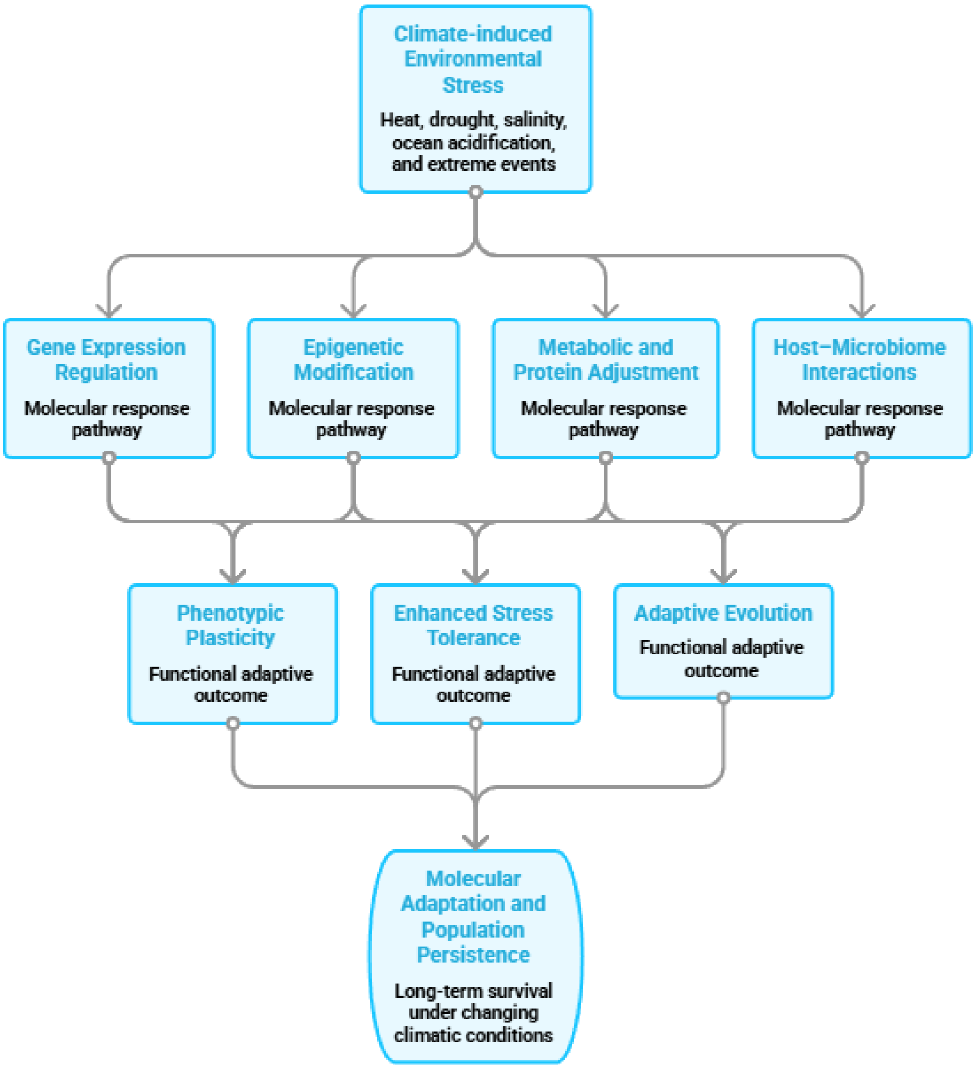

Figure 2. Molecular Mechanisms Underlying Climate Adaptation

5.4 Applications of Genomics, Transcriptomics, and Multi-Omics

The modern omics technologies have revolutionized the study of climate adaptation by providing the ability to analyze genomes, transcriptomes, proteomes, metabolomes and microbial communities in a comprehensive fashion. These strategies enable the discovery of genes, regulatory pathways, and networks that are adaptive and resilient to climate change in a wide range of species. The importance of genomics cannot be overemphasized for biodiversity conservation, ecological restoration and identifying populations with high adaptive potential for future climate conditions (Breed et al., 2019). The advent of molecular breeding, genome editing, and multi-omics technologies is driving the creation of climate-smart crop varieties for agriculture that hold the promise of sustaining productivity amidst rising environmental stresses (Mersha et al., 2026). Moreover, remote sensing technologies used to supplement molecular tools, allowing for broad-scale monitoring of ecosystem structure, vegetation dynamics and habitat changes that impact adaptive processes in tropical forests and other ecosystems (Helmer et al., 2024). Together, these technological advances enable the reinforcement of conservation planning and offer strong options for reducing the pervasive biodiversity loss linked to anthropogenic climate change (Brondízio et al., 2019). Table 2 provides an overview of major omics technologies that are currently being used to study molecular adaptation and climate resilience in a variety of biological systems.

Table 2. Multi-Omics Technologies Applied in Climate Adaptation Research

Technology	Primary Application	Contribution to Climate Research	Reference
Genomics	Adaptive gene identification	Climate adaptation studies	(Bernatchez et al., 2024)
Transcriptomics	Gene expression profiling	Stress-response analysis	(Thangaraj & Sun, 2026)
Epigenomics	DNA methylation studies	Phenotypic plasticity	(Uddin et al., 2026)

Metabolomics	Metabolic pathway analysis	Physiological adaptation	(Mersha et al., 2026)
Remote sensing integration	Ecosystem monitoring	Large-scale biodiversity assessment	(Helmer et al., 2024)

6. Ecosystem Resilience Under Climate Change

6.1 Concept and Indicators of Ecosystem Resilience

Ecosystem resilience is the ability of the ecosystem to cope with climatic disturbances, sustain key functions and rebound from environmental stress. Resilience is often measured under climate change in terms of species richness, functional diversity, genetic diversity, productivity of the ecosystem, landscape connectivity, or ecological network stability. The impacts of climate change span from genes to biomes, impacting ecological organization at various levels and causing a greater risk to ecological services and human welfare (Scheffers et al., 2016). Recent climate-biodiversity syntheses also reveal that resilience needs to be viewed in an integrated ecological, genetic and policy perspective (Zohra, 2026). The IPBES–IPCC workshop also highlighted that biodiversity protection and climate adaptation must go hand in hand, as ecosystem resilience is dependent on ecological integrity and climate mitigation (Pörtner et al., 2021).

6.2 Genetic Diversity as a Foundation of Ecosystem Stability

The adaptive potential of a population in a changing environment is increased with genetic diversity, which in turn increases ecosystem stability. A wider diversity of alleles in a population provides a higher likelihood of alleles that are tolerant to heat, drought, disease and habitat disturbance. Genetic redundancy is particularly significant because it involve multiple genetic pathways that enable similar adaptive functions and help populations remain evolutionarily flexible amid changes in the environment (Láruson et al., 2020). Genomics-based conservation policies, via identification of adaptive potential and informing species management, enhance resilience (Funk et al., 2019). Likewise, the ability to predict future adaptive responses makes predictive evolutionary genomics a valuable asset for proactive planning of biodiversity (Ortiz-Barrientos et al., 2025). An ecosystem approach to tree breeding and genetic improvement of trees can also help build climate-tolerant forest populations (Jaliya, 2024).

6.3 Species Interactions, Functional Diversity, and Ecological Recovery

Species interaction and functional diversity are also crucial in ecosystem resilience. Pollination, predation, competition, decomposition and mutualistic relationship are responsible to maintain ecological balance and recovery after disturbance. Such interactions can be disrupted by climate change through changes in species distribution and phenology and changes in population connectivity. Both structural and functional properties were integrated to assess ecological network sustainability, thereby predicting its performance in the future climate scenario (Sun et al., 2024). Landscape connectivity planning is therefore important as continuity of habitat allows species to move, gene flow, recolonization and ecological recovery in the face of future climate and land-use change (Costanza & Terando, 2019). However, earth observation technologies also used to enhance the ability to monitor biodiversity and genetic diversity on a larger scale and to assess resilience across landscapes (Schuman et al., 2024). Figure 3 shows the combined contribution of genetic, functional, ecological and species diversity, to resilience and recovery of ecosystems after climatic disturbances.

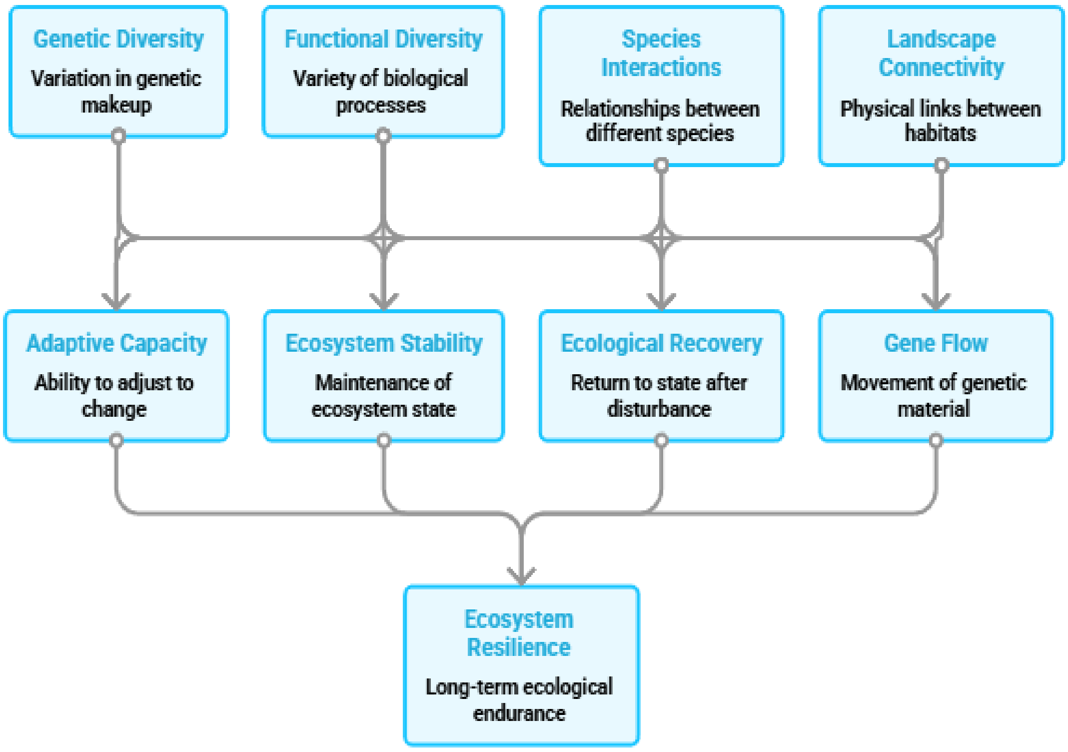

Figure 3. Components of Ecosystem Resilience under Climate Change

6.4 Ecosystem Tipping Points and Long-Term Resilience

Ecosystems moving past tipping points, past which recovery is difficult or impossible, threaten long-term resilience. Loss of biodiversity, genetic erosion, habitat fragmentation and loss of ecological interactions may increase the vulnerability of ecosystems to future disturbances. Genetic mixing assisted gene flow, and provenancing increase adaptive potential of vulnerable populations and lower their risk of extinction from climate change (Hoffmann et al., 2021). More comprehensive biodiversity valuation approaches also underpin the ecological, cultural, economic and social significance of ecosystem resilience (Islar et al., 2022). Thus, to build long-term resilience, we need to consider genetic conservation, ecological restoration, landscape connectivity and policies that are sensitive to climate change. Table 3 provides a summary of commonly used indicators for assessing ecosystem resilience and their relevance for climate adaptation and biodiversity conservation.

Table 3. Indicators Commonly Used to Assess Ecosystem Resilience

Indicator	Ecological Significance	Climate Adaptation Relevance	Reference
Genetic diversity	Evolutionary potential	Adaptive capacity	(Láruson et al., 2020)
Functional diversity	Ecosystem functioning	Ecological stability	(Sun et al., 2024)
Landscape connectivity	Species dispersal	Gene flow maintenance	(Costanza & Terando, 2019)
Ecological network integrity	Community resilience	Ecosystem recovery	(Pörtner et al., 2021)
Biodiversity index	Ecosystem health	Long-term monitoring	(Islar et al., 2022)

7. Conservation Strategies and Climate Adaptation

7.1 Climate-Smart Conservation Approaches

Climate-smart conservation combines the approach of biodiversity management with climate adaptation, fostering the resilience of species and ecosystems in the face of a rapidly shifting climate. Climate-smart conservation differs from more traditional conservation strategies by prioritizing adaptive management, landscape connectivity, ecosystem-based adaptation and integrating climate projections into conservation planning. They are all examples of strategies aimed at enhancing species ability to adapt to future environmental variations, and to continue to provide ecosystem functions and services. With the growing need for prioritizing conservation actions, there is a need to combine ecological, evolutionary and climatic information into predictive models to accurately forecast biodiversity responses (Urban et al., 2016). A recent study also indicates the need for robust evidence on genetic adaptation to enhance conservation planning and the development of more effective climate adaptation strategies for wild populations (van Dis, 2024).

7.2 Assisted Gene Flow and Assisted Evolution

The use of assisted gene flow and assisted evolution has become a viable conservation tool for the improvement of adaptive capacity in climate change threatened populations. Assisted gene flow is the intentional transfer of individuals or genetic material between populations to boost adaptive genetic diversity, while assisted evolution includes selective breeding, experimental evolution or manipulation of the microbiome to speed up the pace of climate adaptation. Such methods are especially useful for species with low dispersal potential and/or fragmented populations where adaptation to environmental change may be too slow. The host microbe interactions in climate adaptation illustrated in the marine realm, where manipulation of coral associated microbiomes has shown significant promise for enhancing thermal tolerance and resilience to ocean warming and acidification (van Oppen & Blackall, 2019). These serve as complementary measures to aid species persistence and minimize the risk of biodiversity loss under future climate scenarios.

7.3 Ecological Restoration and Genetic Resource Conservation

The use of genetic resource conservation in ecological restoration becomes more common, to improve ecosystem recovery and long-term resilience. Maintaining adaptive genetic diversity is now part of restoration programs that aim to ensure healthy populations that can cope with future climate. Of special consideration are soils, whose physical, chemical and biological characteristics affect the cycling of nutrients, establishment of vegetation and productivity of the ecosystem, and which are affected by climate change. In-depth assessments reveal that the degradation of soil properties due to climate change will create a problem for sustainable land use, highlighting the need for restoration initiatives that consider the ecological and genetic aspects of soil health (Abebaw & Feleke, 2026). In the same way, the impact of climate change on soil microbiomes affects carbon cycling, nutrient availability and ecosystem functioning, and consequently the conservation of soil microbes becomes a more and more important part of restoration and climate adaptation plans (Naylor et al., 2020). The protection of both aboveground and belowground diversity thus contributes to increased ecological resilience and success in ecosystem restoration.

7.4 Emerging Technologies for Biodiversity Monitoring and Conservation

The pace of technological development is accelerating and is revolutionizing biodiversity monitoring and conservation through more detailed monitoring of ecological and genetic responses to climate change. Technologies such as high throughput sequencing, environmental DNA, remote sensing, artificial intelligence, bioinformatics and integrated omics platforms open new doors to track biodiversity at multiple biological scales. These technologies enable early signs of population reductions, adaptive genetic variation and assessment of ecosystem health detected, in support of evidence-based conservation decisions. Recently, there is a call to shift beyond genomics towards the adoption of more translational biodiversity approaches which combine molecular biology, ecological monitoring, environmental data and conservation policy to ensure achieving tangible biodiversity outcomes in the context of global change (Papakostas et al., 2025). Combining these new technologies with the conservation strategies of the climate-smart approach is likely to enhance adaptive management, increase the resilience of ecosystems, and facilitate better conservation planning in a world of rapidly changing climate. Table 4 presents emerging technologies that are improving biodiversity monitoring, adaptive conservation and climate-resilient ecosystem management.

Table 4. Emerging Technologies for Climate-Smart Conservation and Biodiversity Monitoring

Technology	Major Application	Conservation Benefit	Reference
Environmental DNA (eDNA)	Species detection	Early biodiversity monitoring	(Papakostas et al., 2025)
Artificial Intelligence	Predictive habitat modeling	Conservation planning	(Urban et al., 2016)
Remote sensing	Habitat and vegetation assessment	Landscape-scale monitoring	(Schuman et al., 2024)
Genome editing	Climate-resilient species development	Adaptive conservation	(Mersha et al., 2026)
Predictive evolutionary genomics	Forecasting adaptive responses	Climate adaptation planning	(Ortiz-Barrientos et al., 2025)

8. Challenges, Knowledge Gaps, and Future Research Directions

Despite the advances in climate genomics and conservation biology, there are still several scientific and technical challenges that constrain the understanding of climate-driven genetic and ecological responses. A lot of studies are geographically constrained to temperate areas, and tropical, freshwater and polar environments are underrepresented. Still, there are few genomic datasets available that connect molecular adaptation to impacts at the level of the ecosystem, and current tools to predict persistence of species in future climate scenarios are limited. Moreover, the joint analysis of genomic, ecological, physiological, and environmental data is limited, which hinders the creation of powerful predictive models. There is also a lack of standardized approaches to measure adaptive genetic variation, epigenetic responses and ecosystem resilience across a variety of taxa, which limits comparability among studies.

Future research should focus on multidisciplinary research that combines genomics, transcriptomics, epigenomics, remote sensing, artificial intelligence, and ecological modelling to better understand the adaptation to climate change across biological scales. Increased long-term monitoring, development of conservation genetics tools for non-model species and international partnerships improve conservation planning and biodiversity management. There is also a need to put more focus on translating molecular discoveries into practical conservation strategies, such as ‘climate-smart restoration’, ‘assisted evolution’ and ‘adaptive genetic management’. These integrated approaches lead to increased resilience of ecosystems, better evidence-based policy making, and help to conserve biodiversity in the face of accelerating climate change.

9. CONCLUSION

Climate change can change biological systems and their genetic diversity, molecular adaptation, and ecosystem resilience on various scales of space and time. This study clearly indicates from the evidence that genetic diversity is central to species persistence as it allows them to adapt to fast changing environmental conditions. Climate adaptation now includes a significant understanding of the molecular mechanisms involved, thanks to advances in genomics, transcriptomics, epigenetics and other multi-omics technologies, as well as powerful tools for monitoring biodiversity and planning conservation actions. Resilience also relies on functional diversity, ecological connectivity, and maintenance of adaptive genetic variation for long-term ecosystem stability, in addition to species diversity, at the ecosystem level. Conservation strategies, such as climate-smart approaches, assisted gene flow and ecological restoration, and the incorporation of genomics into conservation management, present opportunities to enhance adaptive capacity and support the conservation of biodiversity in the face of future climate change. Still, there are also many outstanding issues, such as the scarcity of long-term genomics data, the limited understanding of adaptive mechanisms in many non-model species, and the lack of integration of the molecular, ecological and environmental data. Interdisciplinary research, international collaboration and evidence-based policy are all critical in filling these gaps and improving ecosystem resilience and biodiversity protection. Evolutionary biology, molecular ecology, and conservation science are key components of the framework of climate adaptation, to ensure sustainable ecosystem management and the ecological services that support natural systems and human societies.

REFERENCES

1. Abebaw, S. E., & Feleke, T. G. (2026). Systematic Review on the Impact of Climate Change on Soil Properties: Implications for Sustainable Land Management. Applied and Environmental Soil Science, 2026(1), 9005763. https://doi.org/10.1155/aess/9005763
2. Aitken, S. N., & Bemmels, J. B. (2016). Time to get moving: Assisted gene flow of forest trees. Evolutionary Applications, 9(1), 271–290. https://doi.org/10.1111/eva.12293
3. Bay, R. A., Harrigan, R. J., Underwood, V. L., Gibbs, H. L., Smith, T. B., & Ruegg, K. (2018). Genomic signals of selection predict climate-driven population declines in a migratory bird. Science, 359(6371), 83–86. https://doi.org/10.1126/science.aan4380
4. Bernatchez, L., Ferchaud, A.-L., Berger, C. S., Venney, C. J., & Xuereb, A. (2024). Genomics for monitoring and understanding species responses to global climate change. Nature Reviews Genetics, 25(3), 165–183.
5. Bourne, D. G., Morrow, K. M., & Webster, N. S. (2016). Insights into the Coral Microbiome: Underpinning the Health and Resilience of Reef Ecosystems. Annual Review of Microbiology, 70(1), 317–340. https://doi.org/10.1146/annurev-micro-102215-095440
6. Breed, M. F., Harrison, P. A., Blyth, C., Byrne, M., Gaget, V., Gellie, N. J., Groom, S. V., Hodgson, R., Mills, J. G., & Prowse, T. A. (2019). The potential of genomics for restoring ecosystems and biodiversity. Nature Reviews Genetics, 20(10), 615–628.
7. Brondízio, E. S., Settele, J., Diaz, S., & Ngo, H. T. (2019). Global assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES. http://icsfarchives.net/21551/
8. Coates, D. J., Byrne, M., & Moritz, C. (2018). Genetic diversity and conservation units: Dealing with the species-population continuum in the age of genomics. Frontiers in Ecology and Evolution, 6, 165.
9. Costanza, J. K., & Terando, A. J. (2019). Landscape Connectivity Planning for Adaptation to Future Climate and Land-Use Change. Current Landscape Ecology Reports, 4(1), 1–13. https://doi.org/10.1007/s40823-019-0035-2
10. Des Roches, S., Pendleton, L. H., Shapiro, B., & Palkovacs, E. P. (2021). Conserving intraspecific variation for nature's contributions to people. Nature Ecology & Evolution, 5(5), 574–582.
11. Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., … Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science, 366(6471), eaax3100. https://doi.org/10.1126/science.aax3100
12. Exposito-Alonso, M., Booker, T. R., Czech, L., Gillespie, L., Hateley, S., Kyriazis, C. C., Lang, P. L. M., Leventhal, L., Nogues-Bravo, D., Pagowski, V., Ruffley, M., Spence, J. P., Toro Arana, S. E., Weiß, C. L., & Zess, E. (2022). Genetic diversity loss in the Anthropocene. Science, 377(6613), 1431–1435. https://doi.org/10.1126/science.abn5642
13. Foden, W. B., Young, B. E., Akçakaya, H. R., Garcia, R. A., Hoffmann, A. A., Stein, B. A., Thomas, C. D., Wheatley, C. J., Bickford, D., Carr, J. A., Hole, D. G., Martin, T. G., Pacifici, M., Pearce-Higgins, J. W., Platts, P. J., Visconti, P., Watson, J. E. M., & Huntley, B. (2019). Climate change vulnerability assessment of species. WIREs Climate Change, 10(1), e551. https://doi.org/10.1002/wcc.551
14. Forester, B. R., Lasky, J. R., Wagner, H. H., & Urban, D. L. (2018). Comparing methods for detecting multilocus adaptation with multivariate genotype–environment associations. Molecular Ecology, 27(9), 2215–2233. https://doi.org/10.1111/mec.14584
15. Funk, W. C., Forester, B. R., Converse, S. J., Darst, C., & Morey, S. (2019). Improving conservation policy with genomics: A guide to integrating adaptive potential into U.S. Endangered Species Act decisions for conservation practitioners and geneticists. Conservation Genetics, 20(1), 115–134. https://doi.org/10.1007/s10592-018-1096-1
16. Gaitán-Espitia, J. D., & Hobday, A. J. (2021). Evolutionary principles and genetic considerations for guiding conservation interventions under climate change. Global Change Biology, 27(3), 475–488. https://doi.org/10.1111/gcb.15359
17. Gienapp, P., & Merilä, J. (2018). Evolutionary responses to climate change. In Encyclopedia of the Anthropocene (pp. 51–59). Elsevier BV. https://pure.knaw.nl/portal/en/publications/evolutionary-responses-to-climate-change/
18. Helmer, E. H., Goodwin, N. R., Gond, V., Souza, C. M., & Asner, G. P. (2024). Characterizing tropical forests with multispectral imagery. In Remote Sensing Handbook, Volume IV (pp. 3–46). CRC Press. https://api.taylorfrancis.com/content/chapters/edit/download?identifierName=doi&identifierValue=10.1201/9781003541172-2&type=chapterpdf
19. Hoffmann, A. A., Miller, A. D., & Weeks, A. R. (2021). Genetic mixing for population management: From genetic rescue to provenancing. Evolutionary Applications, 14(3), 634–652. https://doi.org/10.1111/eva.13154
20. Islar, M., Balvanera, P., Kelemen, E., Pascaul, U., Subramanian, S. M., Nakangu, B., Kosmus, M., Nuesiri, E., de Vos, A., & Porter-Bolland, L. (2022). Methodological assessment report on the diverse values and valuation of nature of the intergovernmental science-policy platform on biodiversity and ecosystem services.: Chapter 6: policy options and capacity development to operationalize the inclusion of diverse values of nature in decision-making. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). https://doi.org/10.5281/zenodo.6522359.
21. Jaliya, R. (2024). Advances in tree breeding and genetics (pp. 378–399).
22. Keller, S. R., Fitzpatrick, M. C., Lachmuth, S., Mosher, D., Capblancq, T., Potter, K. M., Byers, E. A., & Butnor, J. R. (2026). Climate Change Implications and Adaptation Solutions. In D. J. Brown, M. A. Thomas-Van Gundy, C. A. Diggins, A. Silvis, & K. M. Shallows (Eds.), Ecology and Restoration of Red Spruce Ecosystems in the Central and Southern Appalachians (pp. 219–259). Springer Nature Switzerland. https://doi.org/10.1007/978-3-032-19616-3_7

23. Kremer, A., Chen, J., & Lascoux, M. (2024). Are forest trees genetically resilient? https://hal.science/hal-04775124/
24. Laikre, L., Hoban, S., Bruford, M. W., Segelbacher, G., Allendorf, F. W., Gajardo, G., Rodríguez, A. G., Hedrick, P. W., Heuertz, M., Hohenlohe, P. A., Jaffé, R., Johannesson, K., Liggins, L., MacDonald, A. J., OrozcoterWengel, P., Reusch, T. B. H., Rodríguez-Correa, H., Russo, I.-R. M., Ryman, N., & Vernesi, C. (2020). Post-2020 goals overlook genetic diversity. Science, 367(6482), 1083–1085. https://doi.org/10.1126/science.abb2748
25. Láruson, Á. J., Yeaman, S., & Lotterhos, K. E. (2020). The importance of genetic redundancy in evolution. Trends in Ecology & Evolution, 35(9), 809–822.
26. Legg, S. (2021). IPCC, 2021: Climate change 2021-the physical science basis. Interaction, 49(4), 44–45.
27. Leigh, D. M., Hendry, A. P., Vázquez-Domínguez, E., & Friesen, V. L. (2019). Estimated six per cent loss of genetic variation in wild populations since the industrial revolution. Evolutionary Applications, 12(8), 1505–1512. https://doi.org/10.1111/eva.12810
28. Yousefi, M., Kafash, A., Valizadegan, N., Ilanloo, S. S., Rajabizadeh, M., Malekoutikhah, S., Yousefkhani, S. S. H., & Ashrafi, S. (2019). Climate Change is a Major Problem for Biodiversity Conservation: A Systematic Review of Recent Studies in Iran. Contemporary Problems of Ecology, 12(4), 394–403. https://doi.org/10.1134/S1995425519040127
29. Mersha, K. Y., Muktar, M. S., Negawo, A. T., Mulat, M. W., & Abebe, F. M. (2026). Accelerating climate resilient agriculture through the integration of molecular breeding with genome editing and omics approaches. Discover Agriculture, 4(1), 167. https://doi.org/10.1007/s44279-026-00615-2
30. Miller, T. C., Miller, M. J., Giles, E. C., Jeffs, A., Sabadel, A. J. M., Laroche, O., & Pochon, X. (2026). Genetic research to guide conservation and the understanding of freshwater eels of the genus Anguilla: A bibliographic analysis. Canadian Journal of Fisheries and Aquatic Sciences, 83, 1–15. https://doi.org/10.1139/cjfas-2025-0370
31. Naylor, D., Sadler, N., Bhattacharjee, A., Graham, E. B., Anderton, C. R., McClure, R., Lipton, M., Hofmockel, K. S., & Jansson, J. K. (2020). Soil Microbiomes Under Climate Change and Implications for Carbon Cycling. Annual Review of Environment and Resources, 45(1), 29–59. https://doi.org/10.1146/annurev-environ-012320-082720
32. Ortiz-Barrientos, D., James, M. E., Yang, L., Bock, D. G., Exposito-Alonso, M., & Rieseberg, L. H. (2025). Predictive Evolutionary Genomics: Principles, Validation, and Practice. https://ecoevorxiv.org/repository/view/9891/
33. Osmolovsky, I. (2025). Shifting high and low: The role of biotic and abiotic factors in range shifts in response to climate change [PhD Thesis, UNSW Sydney]. https://unsworks.unsw.edu.au/entities/publication/3587d6f1-d66e-43b9-8a91-041b881269b3
34. Papakostas, S., Schenekar, T., & Ahi, E. P. (2025). Translational biodiversity beyond genomics: Toward systemic action. https://ecoevorxiv.org/repository/view/10357/
35. Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., & Cheung, W. L. W. (2021). Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. https://researchers.mq.edu.au/en/publications/scientific-outcome-of-the-ipbes-ipcc-co-sponsored-workshop-on-bio/
36. Razgour, O., Forester, B., Taggart, J. B., Bekaert, M., Juste, J., Ibáñez, C., Puechmaille, S. J., Novella-Fernandez, R., Alberdi, A., & Manel, S. (2019). Considering adaptive genetic variation in climate change vulnerability assessment reduces species range loss projections. Proceedings of the National Academy of Sciences, 116(21), 10418–10423. https://doi.org/10.1073/pnas.1820663116
37. Scheffers, B. R., De Meester, L., Bridge, T. C. L., Hoffmann, A. A., Pandolfi, J. M., Corlett, R. T., Butchart, S. H. M., Pearce-Kelly, P., Kovacs, K. M., Dudgeon, D., Pacifici, M., Rondinini, C., Foden, W. B., Martin, T. G., Mora, C., Bickford, D., & Watson, J. E. M. (2016). The broad footprint of climate change from genes to biomes to people. Science, 354(6313), aaf7671. https://doi.org/10.1126/science.aaf7671
38. Schuman, M. C., Röösli, C., Mastretta-Yanes, A., Helfenstein, I. S., Selmoni, O., Vernesi, C., Millette, K. L., Tobón-Niedfeldt, W., Albergel, C., & Leigh, D. M. (2024). Leveraging earth observation to monitor genetic diversity from space. https://ecoevorxiv.org/repository/view/7274/
39. Shaw, R. E., Elliott, C. P., Coates, D. J., Ottewell, K. M., Segelbacher, G., Mergeay, J., Farquharson, K. A., & Grueber, C. E. (2026). Halting genetic diversity loss, from local to international action and policy. Nature Reviews Biodiversity, 1–15.
40. Shaw, R. E., Farquharson, K. A., Bruford, M. W., Coates, D. J., Elliott, C. P., Mergeay, J., Ottewell, K. M., Segelbacher, G., Hoban, S., & Hvilsom, C. (2025). Global meta-analysis shows action is needed to halt genetic diversity loss. Nature, 638(8051), 704–710.
41. Sun, H., Yin, H., Kong, F., Shen, Z., & Su, J. (2024). Integrating the functions and structures to assess ecological network sustainability under climate change scenarios. Landscape Ecology, 39(2), 20. https://doi.org/10.1007/s10980-024-01799-y
42. Supple, M. A., & Shapiro, B. (2018). Conservation of biodiversity in the genomics era. Genome Biology, 19(1), 131. https://doi.org/10.1186/s13059-018-1520-3
43. Thangaraj, S., & Sun, J. (2026). Omics insights into ocean health: Molecular adaptations and ecosystem resilience under climate stress. Advances in Climate Change Research, 17(1), 199–217.
44. Tonkin, J. D., Siqueira, T., Merder, J., Datry, T., Poff, N. L., Talbot-Jones, J., & Olden, J. D. (2026). Extreme events and river biodiversity under climate change. Nature Reviews Biodiversity, 2(3), 150–169.

45. Uddin, T., Zohora, F. T., Khanam, T., Akter, M., Himika, L. I., Aziz, A. T., Tabassum, F., Tushy, S. M. K., Aktar, S., & Misha, M. M. (2026). Climate Change-Induced Stress and Neural Plasticity: Genetic and Epigenetic Mechanisms of Adaptation. OBM Genetics, 10(2), 1–28.
46. Urban, M. C., Bocedi, G., Hendry, A. P., Mihoub, J.-B., Pe'er, G., Singer, A., Bridle, J. R., Crozier, L. G., De Meester, L., Godsoe, W., Gonzalez, A., Hellmann, J. J., Holt, R. D., Huth, A., Johst, K., Krug, C. B., Leadley, P. W., Palmer, S. C. F., Pantel, J. H., … Travis, J. M. J. (2016). Improving the forecast for biodiversity under climate change. Science, 353(6304), aad8466. https://doi.org/10.1126/science.aad8466
47. van Dis, N. E. (2024). Genetic adaptation to climate change in wild populations: A systematic literature review identifies opportunities to strengthen our evidence base. https://ecoevorxiv.org/repository/view/7634/
48. van Oppen, M. J., & Blackall, L. L. (2019). Coral microbiome dynamics, functions and design in a changing world. Nature Reviews Microbiology, 17(9), 557–567.
49. Vidić, R., Chatelain, M., Smith, O. M., Szulkin, M., Zanko, D., Lussier, N., Mizuno, A., Dominoni, D. M., Visser, M. E., & Nakagawa, S. (2026). Synthesis of Anthropogenic Impacts on Birds-Systematic Map and Bibliometric Analysis of Meta-Analyses. https://ecoevorxiv.org/repository/view/12878/
50. Waldvogel, A.-M., Feldmeyer, B., Rolshausen, G., Exposito-Alonso, M., Rellstab, C., Kofler, R., Mock, T., Schmid, K., Schmitt, I., & Bataillon, T. (2020). Evolutionary genomics can improve prediction of species' responses to climate change. Evolution Letters, 4(1), 4–18.
51. Williams, J. W., Ordonez, A., & Svenning, J.-C. (2021). A unifying framework for studying and managing climate-driven rates of ecological change. Nature Ecology & Evolution, 5(1), 17–26.
52. Zattara, E. E., & Aizen, M. A. (2021). Worldwide occurrence records suggest a global decline in bee species richness. One Earth, 4(1), 114–123.
53. Zohra, F. F. (2026). Mapping the climate-biodiversity knowledge system: A 35-year bibliometric analysis using OpenAlex (1990–2024). ARPHA Preprints, 7, e203945.