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Review Article

Resilience of forests in a changing climate: Responses, mechanisms, and adaptations

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Abstract

Forest ecosystems are increasingly vulnerable to environmental changes, including rising temperatures, shifting precipitation patterns, and persistent water stress. These changes disrupt essential physiological processes such as photosynthesis, transpiration, and nutrient uptake, directly impacting forest productivity, species distribution, and carbon sequestration capacity. Moreover, fluctuations in temperature and water availability influence tree growth trends, contributing to biodiversity loss and altering ecosystem dynamics. At the molecular level, trees exhibit gene expression modifications in response to climatic stressors, indicating potential adaptation mechanisms. This review explores the complex interactions between forest ecosystems and environmental changes, emphasizing key processes such as nutrient cycling, soil health, and microbial activity. We analyze the effects of extreme temperatures, drought, and excessive rainfall on tree physiology and ecosystem stability, highlighting species-specific adaptive strategies, including altered nutrient allocation, root modifications, and physiological adjustments. Additionally, we discuss human interventions such as targeted fertilization, biochar application, and sustainable land management as potential mitigation strategies to enhance forest resilience. Understanding the physiological, morphological, and molecular responses of forests to climate variability is crucial for developing adaptive management strategies. By integrating scientific insights into forest conservation and management, this review proposes innovative approaches to safeguard forest ecosystems against environmental stressors, ensuring their long-term sustainability and continued role in global climate regulation.

Keywords: adaptation; ecosystems; nutrient cycling; photosynthesis; resilience

Introduction

Forests play a fundamental responsibility in retaining environmental balance, regulating the global climate, and supporting a vast array of ecosystems (Larjavaara *et al*., 2021). However, the accelerating pace of

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environmental changes has triggered significant physiochemical transformations within forest ecosystems. Shifting weather patterns, rising global temperatures, and an increasing frequency of extreme events are threatening the stability of forests, which are critical to carbon sequestration (Psistaki *et al*., 2024). The current climate crisis, characterized by elevated temperatures and higher Co_2 levels, extremely impacts the physiological and morphological processes of forests. These changes also disrupt the intricate interactions among pests, natural enemies, competitors, and mutualists within these ecosystems (Liebhold *et al*., 2017).

In regions where water availability is not an issue, increased N deposition and rising CO_2 may encourage tree growth and carbon storage (Adams, 2021). However, water constraint, increasing competition from rising CO_2, and warmer temperatures have led to a drop in net above-ground biomass change and an increase in tree mortality (Seidl and Turner, 2022). One of the most visible influences of environmental changes is its effect on tree and sapling growth within natural forests. Rising temperatures have led to shifts in phenological events, such as earlier bud bursts, leafing, and flowering, although significant regional and annual variations persist (Tiwari *et al*., 2021). These phenological changes not only alter forest dynamics but also increase the vulnerability of trees to infestations (Tiwari *et al*., 2021). Additionally, environmental changes influence forests' roles in carbon cycling, modifying their capacity for carbon sequestration and altering natural disturbance regimes, such as fire and insect outbreaks (Dye *et al*., 2024). These shifts in disturbance patterns, observed across many forest ecosystems, are projected to intensify and remain among the many profound consequences of environmental changes in the approaching decades (Larjavaara *et al*., 2021).

The ability of forests to acclimate or adjust to evolving climatic conditions is largely dependent on their physiological processes and adaptive capacity. Key traits, such as the regulation of bud flush, exhibit significant phenotypic plasticity, serving as a crucial mechanism for short-term adaptation to environmental variability (Klisz *et al*., 2023). However, while phenotypic plasticity allows trees to respond dynamically to immediate changes, genetic diversity plays a fundamental role in determining long-term resilience. Studies indicate that plasticity alone may be insufficient to ensure optimal fitness across heterogeneous and rapidly changing climatic conditions (Rawat *et al*., 2020). Rapid climate shifts pose significant challenges for forest ecosystems, particularly because trees, as long-lived and sessile organisms, are often genetically adapted to their specific local climates. Unlike mobile species that can migrate to more suitable environments, many tree species face substantial constraints in relocating to optimal habitats. Consequently, their survival is increasingly threatened by their limited capacity to shift distributions or evolve quickly enough to cope with accelerating climate change (Isabel *et al*., 2020). This underscores the urgent need for conservation strategies that promote genetic diversity, facilitate assisted migration, and support ecosystem resilience in the face of ongoing climatic transformations.

Developing effective solutions to enhance forest resilience requires a deep understanding of how plants and forests respond ecophysiologically to environmental changes. This review examines the drivers and consequences of these changes, highlighting the need for adaptive strategies to mitigate their impacts and ensure the long-term sustainability of forest ecosystems.

Environmental changes and its effects

The delicate balance of forest ecosystems has been upset by environmental changes that are primarily caused by human activities like deforestation and the emission of greenhouse gases. These changes have significantly changed global temperature and precipitation patterns (Dar *et al*., 2020). The dynamics of forests are shaped by these phenomena, which also causes intricate morphological and physiological changes in plant species (Pardi *et al*., 2023).

Worldwide warming is one of the most obvious causes of environmental changes, and it has a significant effect on tree phenological occurrences. As a result of the rising frequency of events like earlier bud bursts, leafing, and flowering, established ecosystem dynamics are being disrupted and crucial biological activities are

occurring at different times (Venäläinen *et al*., 2020). These phenological shifts have a greater impact on forest ecosystems because they frequently ripple into other ecological processes. Concurrently, the rising levels of atmospheric CO_2 have become a significant driver of physiological changes within forest ecosystems. Elevated CO_2 levels, a necessary component of photosynthesis, change the development patterns of trees and the cycling of nutrients, which impacts the general health of forests (Cherubini *et al*., 2021). The viability and resilience of these ecosystems are seriously threatened by the disturbance of the delicate balance of carbon sequestration, a vital ecosystem service that forests supply (Cherubini *et al*., 2021).

Precipitation patterns, another important climatic component, are altering dramatically in the age of environmental change. Rainfall intensity, frequency, and distribution variations have a direct impact on water availability, which in turn has a domino effect on the morphology and physiology of forests (Vacek *et al*., 2023). Extremes like drought stress and waterlogging are becoming more common in forests, which hinder tree growth, change the species composition, and weaken ecosystem resilience (Menezes-Silva *et al*., 2019). Communities and ecosystems as a whole, not just particular tree species, are impacted by these climate conditions.

Moreover, biotic relations within forests are undergoing paradigm shifts in response to climate-induced morphological and physiological alterations. Redefining the interactions between pests, their surroundings, and other species, such as mutualists, natural adversaries, and competitors—is underway (Costa *et al*., 2023). The structural and functional integrity of forest ecosystems are further threatened by natural disturbances like wildfires and insect outbreaks, which are made more frequent and intense by environmental changes (Dwivedi and Chandola, 2024). The sustainability of forest ecosystems becomes more and more vulnerable as species compositions change and feedback loops intensify these impacts.

Forest ecosystems are at a turning point in their history, confronting hitherto unheard-of difficulties that call for adaptive solutions due to the complex forces causing environmental changes (Dwivedi and Chandola, 2024). Developing effective conservation and management strategies necessitates a comprehensive understanding of the morphophysiological changes induced by environmental shifts. Forest resilience and long-term adaptability depend on proactive measures that mitigate stress factors and enhance the capacity of ecosystems to withstand changing climatic conditions (Börner *et al*., 2020). The urgency of addressing these environmental challenges and their underlying causes cannot be overstated, as delays in intervention may lead to irreversible biodiversity loss and ecosystem degradation. Successful conservation efforts must extend beyond species-specific approaches and consider broader ecological interactions, including habitat connectivity, species migration patterns, and the role of biodiversity in ecosystem stability. Integrating adaptive management strategies, such as assisted gene flow, habitat restoration, and sustainable land-use practices, is essential for fostering forest resilience in the face of accelerating climate change. A holistic approach that accounts for ecological, genetic, and environmental dynamics will be key to ensuring the sustainability of forest ecosystems for future generations (Dwivedi and Chandola, 2024).

Physiological responses

Environmental changes have numerous effects on forests, triggering various responses at physiological, ecological, and structural levels. Variations in precipitation patterns and rising temperatures cause changes in the species composition, distribution, and forest dynamics, often favoring invasive species or those more tolerant to stress (Khedr and Al-Khayri, 2023). Prolonged droughts and heat stress can weaken trees, increasing their vulnerability to illnesses and pests (El-Beltagi *et al*., 2025a), while extreme weather events such as storms, floods, and wildfires cause significant damage to forest ecosystems. Additionally, changes in atmospheric CO_2 levels influence photosynthesis and growth rates, but these benefits are often offset by nutrient limitations and environmental stressors (El-Beltagi *et al*., 2025b). Forest ecosystems also experience shifts in carbon

sequestration capacity, affecting their role as carbon sinks in mitigating environmental changes. The necessity for adaptive forest management techniques to improve resilience and safeguard biodiversity is highlighted by these cascading impacts (Figure 1).

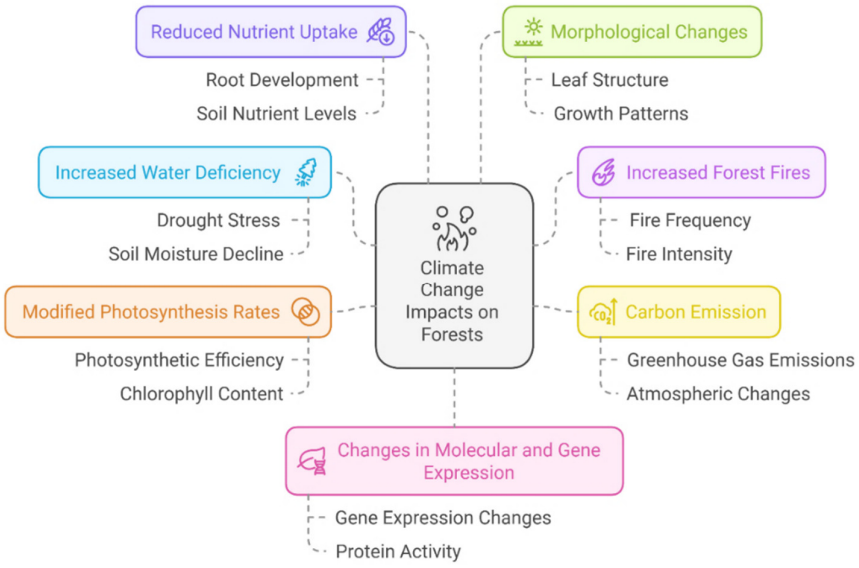

Figure 1. Comprehensive overview of the main effects of environmental changes on forest ecosystems

The Light, heat, CO_2, water, and nutrients are all necessary for trees to continue photosynthesis and flourish. Environmental changes are changing these basic processes, as evidenced by rising temperatures and CO_2 levels. Growing temperatures hasten the organic matter's breakdown in the soil, which improves mineralization and makes more nutrients available for plant absorption. Nevertheless, the combined impacts of high CO_2 and temperature differ according on the characteristics of the soil, the amount of water present, and the availability of nutrients. These forest resources are closely related to tree growth, which affects the ratio of growth to mortality and, in turn, determines forest productivity (Socha *et al.*, 2023). The carbon cycle is significantly impacted over the long term by changes in temperature, precipitation, and atmospheric CO_2 levels, which both directly and indirectly impact the cycling of nutrients (Rastegar and Khedr, 2025). Changes in the hydrological cycle, growing season length, and forest composition all reflect these changes (Zhao *et al.*, 2022). Some of the essential physiological reactions of trees to environmental changes are listed below.

Rise up in water stress

Changes in rainfall patterns and rising temperatures driven by environmental shifts are intensifying water stress in forests, significantly impacting their structure and function. This stress disrupts critical physiological processes, including water uptake, transpiration, and nutrient transport, ultimately affecting tree growth, productivity, and survival. Water availability is a key determinant of ecosystem composition and resilience, influencing species distribution and forest dynamics. For instance, temperate forests, which generally receive between 500 and 2,500 mm of annual precipitation, rely on consistent moisture levels to sustain their biodiversity and ecological balance (Soto *et al.*, 2024). However, prolonged droughts and altered precipitation regimes threaten these ecosystems by reducing soil moisture, increasing tree mortality rates, and making forests more susceptible to pests and diseases. Addressing these challenges requires a deeper understanding of how

forests respond to hydrological changes and the implementation of adaptive management strategies to enhance their resilience (Fuertes *et al*., 2023).

Changes in precipitation models, a defining feature of environmental changes, are contributing to water stress in trees (Li *et al*., 2022). In response, leaves adjust their stomatal conductance to safeguard water, which, unfortunately, also limits the influx of carbon dioxide, a key component for photosynthesis. The intricate correlation between water uptake and photosynthetic activity (osmotic stress, −0.362 MPa) is explored in studies such as Li *et al*. (2022), which reveal the complex mechanisms trees employ to maintain essential physiological functions while coping with water stress. This emphasizes how crucial it is to stay properly hydrated in order to maintain ideal gas exchange and photosynthetic efficiency. Tree species with innate adaptations that enable them to sustain effective photosynthesis even in water-limited conditions are identified by Fuertes *et al*. (2023). These results pave the way for forest management techniques that seek to uncover and breed resilient tree genotypes, which may be essential for preserving forest productivity in the face of increasingly erratic water circumstances. Forest managers can increase forests' tolerance to water stress brought on by climate change by concentrating on species that utilize water efficiently.

Over millennia, plant competition has favored species with adaptations to limited resources, including water. However, increasing drought frequency and severity are challenging these adaptations. Short-term droughts can significantly reduce ecosystem productivity (Gampe *et al*., 2021). Long-term droughts can lead to more severe ecosystem disruptions, including tree mortality from prolonged water stress (Gampe *et al*., 2021). Forest ecosystems are further destabilized by prolonged droughts, which also increases the likelihood of wildfires and insect outbreaks (Singh *et al*., 2024). Certain species or forest types may become less adaptable to environmental stressors because of shifting competitive advantages among tree species brought about by changes in insect species dynamics, outbreak frequency, or fire intensity (Gampe *et al*., 2021).

Reduced carbon sink and persistent water stress

It is commonly known that severe droughts decrease forests' ability to absorb carbon by impairing the widespread impermanence of trees. However, not enough research has been done on how modest but prolonged water stress affects the phenology and physiology of forests. According to recent studies, long-term water stress may reduce deciduous forests' capacity to absorb carbon by up to 20% in the ensuing decades. This decrease is equivalent to the worldwide carbon emissions from fossil fuels and is ascribed to mesophication and prolonged water stress (Cristiano *et al*., 2020). Such decreases in carbon sequestration imply that the growth-promoting effects of higher CO_2 and warmer temperatures may be offset by regional decreases in water availability. Forests may therefore lose their ability to mitigate climate change, highlighting the intricate relationships between environmental change factors and forest dynamics (Cristiano *et al*., 2020).

Physiological impacts of drought and heat

Global warming exacerbates the susceptibility of tree species to drought by affecting their physiological responses in varied ways. In some species, higher temperatures reduce stomatal conductance, leading to lower transpiration rates and higher leaf temperatures. These changes result in diminished photosynthesis rates, increased photorespiration, and elevated respiration rates, collectively impairing the tree's carbon balance (Hartmann *et al*., 2022). Other species, on the other hand, show improved transpiration and greater stomatal conductance in hotter climates. In drought conditions, this increases xylem tension, which raises the danger of cavitation and hydraulic collapse even though it may momentarily chill the leaves. Cavitation causes significant physiological stress and increases the risk of tree mortality by interfering with the plant's ability to transfer water (Hartmann *et al*., 2022; El-Beltagi *et al*., 2025c). These contrasting responses highlight the species-specific nature of tree adaptability to combined heat and drought stress, as well as the importance of understanding physiological trade-offs in maintaining forest resilience under changing climatic conditions.

Modified rates of photosynthesis

The rate of photosynthesis in plants is greatly impacted by environmental changes, mostly due to improved CO_2 levels in the atmosphere. By promoting photosynthesis, the primary mechanism via which carbon inputs the biosphere, CO_2 has a direct effect on plant metabolism. First, increased CO_2 levels have the ability to promote photosynthesis, which could lead to an increase in plant productivity and growth. However, additional elements like high temperatures and water stress frequently counteract this benefit, negating the gains (Tian *et al*., 2024). Forest ecosystems, dominated by plants with C3 photosynthetic pathways, are particularly sensitive to these changes. In C3 plants, elevated CO_2 could temporarily boost carbon storage in forest biomass, counteracting atmospheric CO_2 rise. Limited evidence, such as tree ring studies, suggests that forest growth in certain regions has increased over the past century, although this finding remains debated (Tian *et al*., 2024). The amazing process of photosynthesis, an age-old alchemical reaction that turns sunlight into the basic energy that drives all biological activity, is at the forest ecosystem's vitality. Understanding the subtleties of photosynthesis is essential for figuring out the intricate link between trees and their shifting habitats as a result of environmental changes (Psistaki *et al*., 2024). Through photosynthesis, plants convert carbon dioxide and water into carbohydrates, releasing oxygen as a vital byproduct (Psistaki *et al*., 2024). This fundamental metabolic process not only drives tree growth but also sustains entire forest ecosystems by forming the foundation of the trophic structure. The carbohydrates produced serve as an energy source for herbivores, which in turn support higher trophic levels, creating intricate food webs that sustain biodiversity. Additionally, photosynthesis plays a crucial role in regulating atmospheric carbon levels, highlighting its significance in mitigating climate change. By maintaining forest health and productivity, this process ensures ecological stability and resilience, reinforcing the interdependence between plants, wildlife, and environmental sustainability (Tian *et al*., 2024).

In forest ecosystems, photosynthesis is greatly impacted by the prospect of environmental changes. This crucial process is threatened by several factors, including changing precipitation patterns, rising extreme weather occurrences, and shifting temperature regimes. In the short term, high temperatures can speed up photosynthetic rates, but over time, heat stress can reduce photosynthesis' effectiveness and hinder growth and output (Pollastrini *et al*., 2020). Variations in precipitation make these problems worse by changing the amount of water available, which impacts carbon uptake and photosynthetic efficiency. Since photosynthesis is the cornerstone of forest health, disturbances to this process have an impact on productivity, biodiversity, and the ability of forests to sequester carbon. The capacity of forests to moderate environmental changes may be hampered by such disturbances, highlighting the necessity of thorough knowledge and adaptation measures. Forest ecosystems display a range of adaptive responses to changes in photosynthetic dynamics. Certain species are plastic, changing their photosynthetic rates or leaf properties in response to changing environmental circumstances. Others use techniques to minimize water loss or depend on certain metabolic pathways, which enables them to endure stressful situations. Understanding these species-specific responses is critical for anticipating how forests will adapt with climate-induced changes (Pollastrini *et al*., 2020).

Nutrient uptake

A delicate, interdependent network of nutrient cycles that permits the continuous interchange and recycling of vital components is at the core of healthy forest ecosystems. Every leaf, root, and microbe—from the soaring canopies to the forest floor—contributes to this complex symphony, which is necessary to sustain life and build resilience in forests. A key element of comprehending the resilience of forest ecosystems is the complex interaction between nutrient intake and environmental changes (Psistaki *et al*., 2024). Tree growth, productivity, and adaptation are all impacted by the significant changes in the dynamics of nutrient availability in forest soils brought about by shifting precipitation regimes and temperatures in the global climate (Vacek *et al*., 2023).

The dynamic processes that transfer and change vital components like carbon, nitrogen, phosphorus, and potassium within forest ecosystems are known as nutrient cycles. These cycles connect various elements of the ecosystem, such as living things, soils, waterways, and the atmosphere, through biological, geological, and chemical interactions (Vacek *et al*., 2023). With changes in temperature, precipitation patterns, and extreme weather events impacting nutrient availability, cycling, and use, environmental changes have a substantial impact on nutrient cycles. These alterations may be minor, but they have significant long-term effects on the resilience, health, and functioning of forests (Baldrian *et al*., 2023).

The carbon cycle is one of the basic nutrient cycles that is essential to preserving the health of forests. The backbone of organic matter, carbon, which is obtained through photosynthesis, controls the climate and powers vital biological functions (Baldrian *et al*., 2023). However, changes in the environment have the potential to upset the equilibrium of carbon exchange between the atmosphere, vegetation, soils, and microbial communities. Forest health depends on the cycles of nitrogen, phosphorus, and carbon (Meena *et al*., 2023). While phosphorus, which is necessary for energy transfer and cell structure, travels through soils, waterways, and biota, nitrogen, which is necessary for protein synthesis and growth (Khedr and Khedr, 2023), cycles through organic matter, soils, and the atmosphere. Disruptions to these cycles brought on by climate change may have a domino impact on biodiversity, ecosystem productivity, and nutrient availability (Vacek *et al*., 2023; El-Beltagi *et al*., 2024; El-Beltagi *et al*., 2025d)

Nutrient availability in forest ecosystems is directly impacted by changes in precipitation patterns, including an increase in the frequency and severity of extreme weather events like droughts and heavy rainfall. emphasize how these changes impact the transport and solubility of vital soil nutrients (Al-Khayri *et al*., 2024). Drought reduces microbial activity, which is necessary for nutrient cycling, making nutrients less available. On the other hand, periods of intense rainfall may result in nutrient leaching, which is the removal of important minerals from the soil profile. Tree growth and the general functioning of the ecosystem are seriously hampered by these changes in nutrient availability (Costa *et al*., 2023). Environmental changes are characterized by rising temperatures, which have two effects on the cycling of nutrients in forest ecosystems. Higher temperatures speed up biological processes, increasing microbial breakdown rates and organic matter turnover, according to Hartmann *et al*. (2022). First, this acceleration increases the availability of nutrients, which may encourage the growth of trees. Recognizing the vital role that nutrient availability plays in forest sustainability; researchers are exploring innovative interventions to mitigate nutrient imbalances exacerbated by environmental changes.

As Ongoing research into the complex interactions between environmental changes and forest nutrient uptake underscores the critical need for informed management and policy decisions. As climatic shifts alter nutrient availability, soil composition, and biogeochemical cycles, understanding these dynamics becomes essential for developing effective conservation strategies (Meena *et al*., 2023). The insights gained not only highlight the vulnerabilities of forest ecosystems but also pave the way for sustainable practices that maintain the delicate nutrient balance necessary for long-term forest health and resilience. By integrating scientific knowledge into policy frameworks, stakeholders can implement adaptive strategies that enhance forest adaptation, promote biodiversity, and mitigate the adverse effects of environmental change in an increasingly unpredictable world (Costa *et al*., 2023).

Variations in temperature and photosynthetic rates

The effect of higher temperatures on photosynthesis has garnered significant attention in recent years. Kang *et al*. (2022) emphasize the temperature sensitivity of key enzymes implicated in photosynthesis, particularly Rubisco. As temperatures rise, these enzymes lose their effectiveness, leading to a decline in photosynthetic rates. Mathias and Trugman (2022) further highlight the sensitivity of photosynthesis to increasing temperatures, noting that elevated heat disrupts enzymatic reactions crucial for photosynthesis and impairs the efficiency of carbon fixation processes. As a result, forest canopies experience diminished

photosynthetic capacity, which affects tree growth, productivity, and the ability of forests to sequester carbon. This reduction in photosynthetic activity, in turn, impacts broader ecosystem dynamics.

As temperatures rise, it becomes more challenging to maintain the metabolic equilibrium within tree leaves. High temperatures can upset the delicate balance between light-dependent and light-independent reactions, which lowers photosynthesis's overall efficiency, according to Wang *et al*. (2024). Predicting how various tree species will react to rising temperatures brought on by environmental changes requires an understanding of these molecular pathways. We may better predict how forests may adapt to or suffer with warmer temperatures by examining these intricacies.

Transpiration

In forest ecosystems, transpiration is an essential hydrological activity that shapes the dynamics and resilience of these crucial settings by affecting the equilibrium of water exchange among trees. Interpreting the changing interaction between trees and their ecosystems requires a grasp of the subtleties of transpiration, which becomes increasingly important as environmental changes accelerates. A key component of the forest hydrological cycle is transpiration, which is the flow of water from the roots through the vascular system of the tree and out via stomata on the leaves (Xu *et al*., 2022). This mechanism is essential for sustaining metabolic processes, preserving tree thermoregulation, and moving water and nutrients from the roots to the foliage.

In forest ecosystems, transpiration dynamics are being significantly impacted by environmental changes. Temperature increases, changes in precipitation patterns, and variations in humidity pose a threat to the delicate equilibrium of water exchange (Zhang *et al*., 2022; Khedr *et al*., 2023). High temperatures have the ability to accelerate transpiration, which could exacerbate trees' water stress. Additionally, shifting precipitation patterns lead to uncertainty about the availability of water, which further affects transpirational water loss (Khedr and Khedr, 2024a). Transpiration has far-reaching effects on ecosystem water dynamics, influencing soil moisture, nutrient availability, and atmospheric gas composition, ultimately impacting plant distribution, wildlife habitats, and overall ecosystem resilience (Zhang *et al*., 2022; Khedr and Khedr, 2024b).

In response to changing transpiration dynamics, forest ecosystems display a diverse range of adaptation mechanisms. To adapt to variations in water availability, some species change the stomatal conductance, while others alter the properties of their leaves. In order to survive times of water scarcity, some trees also depend on deep root systems or unique physiological processes. Predicting how forests will react to ongoing environmental changes s requires an understanding of these species-specific adaptations (De Frenne *et al*., 2021). Developing conservation and management measures that improve forest resilience requires an understanding of transpiration's function and susceptibility to environmental changes modifications to forest morphology. The preservation of ecosystems that can adjust to changing transpiration patterns, restoration techniques, and sustainable water resource management are some possible strategies (Dargiri *et al*., 2024; Al-Khayri and Khedr, 2024a).

Modifications to forest morphology

A mix of physiological processes, including photosynthesis, and morphological features, like specific leaf area and stomatal properties, are closely related to how trees grow and adapt to climate change (Kanta *et al*., 2024). The type of forest, local environmental circumstances, and regional climate all influence the specific morphological changes that take place in forests (Figure 2). Furthermore, the effects of environmental changes on forest ecosystems might be made worse by interactions between different environmental stressors.

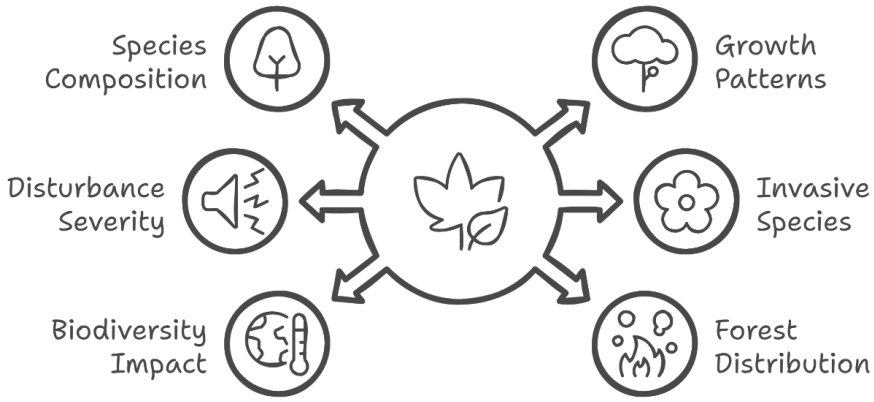

Figure 2. Key morphological changes in forest ecosystems, adaptations and growth responses to climate change

Modified growth trends in forest species

The development patterns and nutrient dynamics of forest plants are directly impacted by variations in temperature and precipitation (Badano *et al*., 2022). While changing precipitation patterns may change the density and geographical distribution of trees, modifying canopy structures and understory dynamics, elevated temperatures might increase evaporation rates, aggravating water stress (Leidinger et al., 2021). As rising temperatures exacerbate low soil moisture conditions and intensify interspecies competition, they also disrupt tree regeneration processes, particularly during the vulnerable seedling stage. Insufficient water availability, combined with heightened competition for limited resources, can reduce seedling survival rates, hinder root establishment, and slow overall growth. These challenges threaten forest regeneration and long-term ecosystem stability, highlighting the need for adaptive management strategies to support seedling establishment under changing climatic conditions (Socha *et al*., 2023; Al-Khayri and Khedr, 2024b). Climate has a significant impact on seed production, germination, and seedling survival, which in turn affects population and community structures (Badano *et al*., 2022). Additionally, climate variability degrades forest resources, leading to increased CO_2 emissions and diminished forest resilience. This further compromises their ability to deliver essential ecosystem services, such as carbon sequestration and biodiversity conservation (Socha *et al*., 2023).

Increased incidence and intensity of unrest

Climate disturbances, including wildfires, insect infestations, storms, and droughts, play a critical role in shaping forest ecosystems. However, as environmental changes drive these events beyond their natural variability, the structural and functional integrity of forests is increasingly disrupted (Burton *et al*., 2020). Forest fires become more intense due to rising temperatures, which decreases forests' ability to absorb carbon (Nunes, 2020). Precipitation levels and forest composition have a direct impact on wildfire frequency, intensity, and patterns. In addition to increasing mortality in older forests under stress from low soil moisture, wildfires also destroy vegetation, disturb wildlife habitats, speed up nutrient cycling, and change the structure of forests (Nunes, 2020).

Shifts in forest distribution

Environmental changes, such as environmental changes, human activity, and natural disturbances, are the main causes of changes in the distribution of forests. While deforestation and alterations in land use split ecosystems, rising temperatures, changed precipitation patterns, and extreme weather events drive forests to

move toward higher latitudes or elevations (Leidinger *et al.*, 2021). These changes lead to decreased ecosystem services like soil fertility and water management, disturbances in carbon sequestration, and a decline in biodiversity. Reforestation, sustainable management, and climate-resilient planting are crucial tactics to lessen these impacts (Rastegar *et al.*, 2024), as are monitoring systems to keep tabs on and adjust to shifts in the distribution and health of forests (Figure 3).

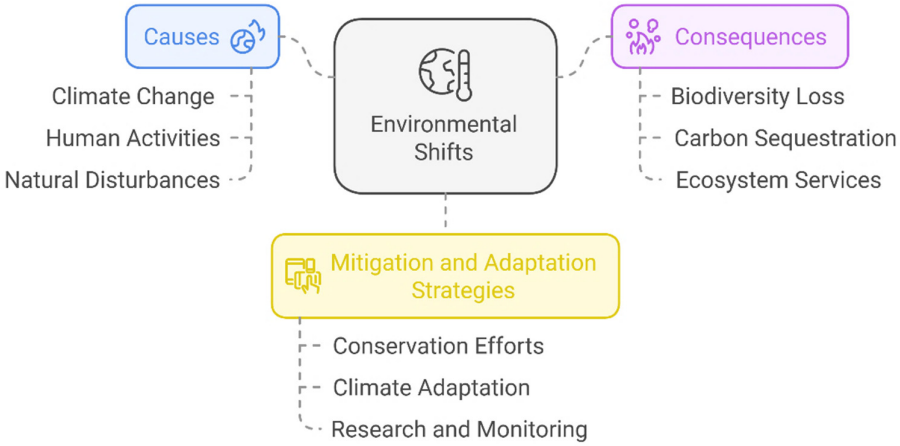

Figure 3. Causes, consequences, and mitigation strategies for shifts in forest distribution

Environmental changes are driving shifts in forest distribution, with many forests migrating poleward or to higher elevations to adapt to modifying climatic conditions. This phenomenon, referred to as "forest migration" (McDowell *et al.*, 2020) significantly impacts biodiversity and ecosystem aid. As global temperatures rise, some tree species are expanding into previously unsuitable habitats, such as higher latitudes or altitudes, benefiting from milder conditions. Not every species, meanwhile, is able to adjust to these shifting circumstances. Higher temperatures in warmer climates may make some tree species' usual habitats unsuitable, which could cause forests to shrink and species composition to change. Some species frequently become more prominent as a result of these changes, while others experience a decline. Because warming temperatures cause permafrost to thaw and destabilize these ecosystems, boreal forests at high northern latitudes are especially vulnerable to the intrusion of species from the south (Kijowska-Oberc *et al.*, 2020).

Changes in the environment have an impact on forests that goes beyond changes in range. Trees are more stressed by rising temperatures and changing precipitation patterns, which makes them more vulnerable to pests, illnesses, and wildfires. Increased mortality rates and deteriorating forest health are caused by these variables. Furthermore, temperature variations may alter the length and timing of growing seasons. Growing seasons may get longer in some places and shorter and less consistent in others (Kijowska-Oberc *et al.*, 2020).

Impact on biodiversity

Forest ecosystems' biodiversity is extremely susceptible to the ripple impacts of environmental changes (Law *et al.*, 2021). Species that are unable to migrate or adapt to more suitable habitats may see population decreases or possibly face local extinction, which could change the makeup of communities and interfere with ecosystem function (Law *et al.*, 2021). By altering patterns of precipitation and temperature, environmental changes are predicted to have a direct impact on the richness and quantity of faunal species. While reptiles are mostly impacted by temperature changes alone, key biodiversity components including trees, birds,

amphibians, and mammals exhibit high relationships with both temperature and precipitation (Law *et al*., 2021). Warming climates are predicted to significantly benefit amphibians in colder areas, such as high-altitude forests. Furthermore, terrestrial invertebrate ranges are already expanding due to global warming (Upadhyay, 2020). Despite challenges, mature forest ecosystems demonstrate significant resistance to change, a phenomenon often described as ecological inertia (Liang and Hurteau, 2023). Rapid species turnover is typically constrained unless a major disturbance, such as the removal of the dominant canopy, disrupts the system. In the absence of such disturbances, competitive interactions gradually shape species replacement over extended periods. This inertia bolsters the resilience and resistance of established forests, enabling them to better withstand the pressures of environmental changes (Liang and Hurteau, 2023). Forest ecosystems' resistance and resilience are essential for maintaining the structural and functional elements required for the conservation of biodiversity. However, there is a serious risk from the indirect consequences of environmental changes, including a rise in disturbances like wildfires. By acting as catalysts, these disruptions accelerate the turnover of species by dispelling inertia. In the process, they frequently result in the destruction of habitat structures that are necessary to preserve the biodiversity that currently exists.

Spread of invasive species

It is anticipated that environmental changes will greatly worsen the frequency, severity, and spread of invasive species, possibly turning once-beneficial species into invasive ones. This change makes it easier for invasive species to enter forest ecosystems through a number of interrelated routes. Environmental changes modify species distribution patterns by removing temperature or moisture constraints, allowing successful invasions into previously unsuitable areas (Srivastava *et al*., 2021). New ecological niches are created as native environments change, giving non-native invasive species the chance to proliferate and spread across new areas. Global shifts in temperature regimes are disrupting ecological equilibria, altering species distributions and community dynamics. While many introduced species initially struggle to survive in non-native environments due to unsuitable climatic conditions, warming temperatures are gradually expanding the habitable range for these species (Moyano *et al*., 2024). This shift increases the likelihood of successful establishment and proliferation of non-native species, potentially leading to invasive behavior that threatens local biodiversity and ecosystem function. The alteration in temperature not only facilitates the survival of imported species but also intensifies competition for resources, alters predator-prey relationships, and increases vulnerability to pests and diseases. Consequently, these changes necessitate proactive management approaches to mitigate the impacts of invasive species and preserve ecosystem integrity in a rapidly warming world (Srivastava *et al*., 2021).

Changes in the composition of species

Many tree species' suitable habitats are changing due to rising temperatures and changed precipitation patterns (Badano *et al*., 2022). While some species increase their range, others experience population reductions or relocate to higher latitudes and elevations. These shifts alter the quantitative and qualitative composition of forests, affecting structure, function, and ecosystem dynamics. Species exhibit unique responses to environmental changes; however, species with similar traits are expected to display comparable adaptive strategies (Tian *et al*., 2024). For instance, angiosperms and gymnosperms exhibit distinct ecophysiological responses to elevated CO_2 levels, which may drive region-specific forest adaptations (Tian *et al*., 2024). Such changes underscore the need to understand how species composition and ecosystem functionality evolve in response to climate stressors.

Molecular and gene expression

Environmental changes exert profound effects on the molecular and genetic turns, influencing organisms across ecosystems. These impacts manifest in diverse and complex ways, altering gene expression patterns in response to shifting environmental factors such as temperature, humidity, and CO_2 levels (Singh, 2024). For example, stress response genes, photosynthesis-related genes, and those regulating flowering time show distinct changes under changed climatic conditions (Lobo *et al*., 2024). Genes associated with thermoregulation, metabolism, and immune responses are also significantly affected, influencing the survival and reproductive success of plants (Blumstein and MacManes, 2024). Additionally, environmental changes induce epigenetic modifications, such as DNA methylation and histone modifications, which regulate gene expression without altering the underlying DNA sequence (Klupczyńska and Ratajczak, 2021). Transgenerational impacts of these epigenetic modifications may increase phenotypic plasticity and adaptability (Klupczyńska and Ratajczak, 2021). Trees use molecular processes to preserve cellular homeostasis and guarantee survival in response to environmental stressors associated with environmental changes. For example, by stabilizing protein folding and inhibiting aggregation, heat shock proteins can shield cells from heat stress (Wei *et al*., 2024). Environmental changes act as selective pressures, triggering evolutionary responses that drive genetic modifications to enhance resistance and tolerance. However, when the rate of environmental change exceeds the pace of adaptation, species may experience maladaptation, leading to mismatches between their genetic traits and shifting ecological conditions (Williams *et al*., 2021). This lag in adaptation increases the risk of population decline and biodiversity loss, particularly for long-lived species such as trees, which have slower generational turnover. Furthermore, environmental changes often interact with additional stressors, such as pollution, habitat fragmentation, and invasive species, compounding physiological and molecular challenges. These combined pressures can disrupt key biological functions, reduce reproductive success, and weaken ecosystem stability, emphasizing the urgent need for conservation strategies that support genetic diversity and adaptive potential.

Conclusions

In conclusion, the resilience of forest ecosystems in the face of environmental changes underscores their complexity and adaptability. However, rising water stress, reduced carbon sinks, and persistent drought conditions are disrupting physiological functions such as photosynthesis, transpiration, and nutrient uptake, thereby affecting forest health and productivity. Variations in temperature further modify photosynthetic rates, altering growth patterns and leading to shifts in species composition. Additionally, forests are experiencing morphological changes, including altered growth trends, increased vulnerability to disturbances, and shifts in distribution. These changes not only impact biodiversity but also facilitate the spread of invasive species, further destabilizing native ecosystems. At the molecular level, gene expression patterns are adapting in response to climatic stressors, highlighting the need for deeper exploration of genetic resilience mechanisms. To mitigate these impacts, it is imperative to implement adaptive forest management strategies that promote sustainable water use, optimize species selection, and enhance carbon sequestration potential. Policies should support conservation efforts that maintain ecosystem stability while fostering biodiversity. Future research should focus on understanding gene-environment interactions to develop climate-resilient forest species. By integrating ecological, physiological, and molecular insights into conservation and management practices, we can safeguard forests against environmental changes, ensuring their continued role in global climate regulation and ecosystem services.

Authors' Contributions

Conceptualization, E.H.K.; visualization, E.H.K., H.S.E-B, and M.M.; investigation, E.H.K., H.S.E-B, and M.A-H; writing-review and editing, E.H.K. and H.S.E-B, and M.A-H.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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