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A Comprehensive Review of the Impact of Climate Change on Plant Growth, Phenology, and Biodiversity

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ABSTRACT

Climate change has emerged as one of the most pervasive drivers of ecological transformation in the twenty-first century, exerting profound and multidimensional effects on terrestrial plant systems. This review synthesizes contemporary evidence on how rising atmospheric carbon dioxide concentrations, warming temperatures, altered precipitation regimes, and increasing frequency of extreme weather events are reshaping plant growth, phenology, and biodiversity. Elevated CO₂ stimulates photosynthetic carbon assimilation and may enhance biomass accumulation through the so-called fertilization effect, yet these gains are frequently constrained by nutrient limitation, water availability, and acclimation responses. Warming temperatures advance the timing of key phenological events such as budburst, flowering, and leaf senescence, generating mismatches between interacting species and disrupting long-established ecological synchrony. At the community level, shifting climatic envelopes are driving poleward and upslope migrations, local extinctions, and the reorganization of species assemblages, with cascading consequences for ecosystem function and the services upon which human societies depend. Drawing on peer-reviewed literature published, this paper examines the physiological mechanisms underpinning plant responses, evaluates the evidence for phenological shifts across biomes, and assesses the implications for biodiversity conservation. The synthesis highlights substantial variability in species' sensitivities and adaptive capacities, underscoring that climate impacts are neither uniform nor universally negative. The review concludes by identifying critical knowledge gaps and proposing future research priorities, including the integration of multi-factor experiments, improved representation of belowground processes, and the development of predictive frameworks that couple physiological, phenological, and population-level responses. A clearer mechanistic understanding of plant climate sensitivity is essential for forecasting ecosystem trajectories and informing adaptive conservation and management strategies.

Keywords: climate change; plant phenology; elevated CO₂; biodiversity; warming; species range shifts; ecosystem function



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1. INTRODUCTION

Plants form the foundation of terrestrial ecosystems, capturing solar energy, cycling nutrients, regulating the hydrological balance, and providing habitat and sustenance for virtually all other organisms. Because they are sessile, plants cannot escape unfavorable conditions and must instead respond physiologically, developmentally, or evolutionarily to environmental change. This intrinsic exposure makes vegetation an especially sensitive sentinel of climatic perturbation. Over the past several decades, anthropogenic greenhouse gas emissions have driven measurable increases in global mean surface temperature, raised atmospheric carbon dioxide concentrations beyond 420 parts per million, and altered the spatial and temporal distribution of precipitation. These changes, individually and in combination, are restructuring the conditions under which plants germinate, grow, reproduce, and disperse. Understanding the breadth of these effects is fundamental to anticipating how ecosystems will function in a warmer world and to designing strategies that safeguard biodiversity and the services it underpins.

The scientific interest in plant responses to climate change has intensified as the evidence base has matured. Long-term observational records, manipulative field experiments, remote sensing, and modeling have collectively revealed that the consequences of climatic change extend from the molecular regulation of stomatal aperture to the continental redistribution of biomes. Yet the picture that emerges is one of considerable complexity and heterogeneity, with responses that vary by species, functional group, biome, and the particular combination of climatic stressors involved. This review brings together recent findings to provide an integrated account of how climate change is influencing three interconnected dimensions of plant biology: growth, phenology, and biodiversity.

1.1 The Climatic Context of Plant Life

The climate system that plants inhabit is being transformed along multiple axes simultaneously. Average temperatures are rising, but so too are the frequency and intensity of heatwaves, droughts, and unseasonal frosts. Precipitation is becoming more variable, with some regions experiencing intensified rainfall and others prolonged aridity. Atmospheric carbon dioxide, the primary substrate of photosynthesis, has risen to concentrations unprecedented in the recent geological past. Each of these drivers interacts with plant physiology in distinct ways, and their combined influence rarely equals the simple sum of their individual effects (Dusenge et al., 2019). Recognizing the multi-factorial nature of the climatic context is essential for interpreting the often-contradictory responses documented across studies, and large-ensemble Earth system modeling has clarified how much of this variability reflects internal climate variability rather than forced trends (Deser et al., 2020).



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1.2 Why Plant Responses Matter

The fate of plant communities under climate change carries implications that reach far beyond botany. Forests and grasslands constitute major terrestrial carbon sinks, and changes in their productivity feed back into the global carbon cycle, either dampening or amplifying future warming. Agricultural systems, which are fundamentally managed plant communities, face threats to yield stability and food security as growing seasons shift and extreme events become more common. Pollination, pest regulation, water purification, and countless other ecosystem services depend on the continued functioning of vegetation and its associated biota. Consequently, the study of plant climate responses is inseparable from broader concerns about ecological resilience and human welfare.

1.3 Defining Growth, Phenology, and Biodiversity

Growth refers to the accumulation of biomass and the developmental progression of plants, encompassing processes such as photosynthesis, respiration, carbon allocation, and resource acquisition. Phenology describes the timing of recurring life-cycle events, including germination, budburst, flowering, fruiting, and senescence, which are tightly coupled to seasonal climatic cues. Biodiversity captures the variety of life at genetic, species, and ecosystem levels, along with the functional roles organisms play within communities. Although treated separately for clarity, these three dimensions are deeply intertwined: altered growth influences competitive outcomes that shape community composition, while phenological shifts can fracture the interactions that sustain biodiversity. This review treats them as facets of a single integrated response.

1.4 Scope and Objectives of the Review

The specific objectives are threefold. First, to elucidate the physiological and developmental mechanisms through which climatic drivers influence plant growth. Second, to evaluate the evidence for phenological shifts and the ecological mismatches they generate. Third, to assess the consequences of climate change for plant biodiversity, including range shifts, local extinctions, and community reorganization. By integrating these strands, the review seeks to clarify the current state of understanding, expose persistent uncertainties, and chart a course for future inquiry. The analysis emphasizes the variability and context-dependence of plant responses, cautioning against simplistic generalizations and highlighting the need for mechanistic, multi-factor approaches.

2. LITERATURE REVIEW

The body of research examining plant responses to climate change has grown substantially, drawing on observational, experimental, and modeling approaches across diverse biomes. The following sections synthesize this literature according to four thematic areas: the effects of elevated carbon dioxide and warming on plant growth, the phenological consequences of



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climatic change, the implications for biodiversity and species distributions, and the role of extreme events and multi-stressor interactions.

2.1 Elevated CO₂, Warming, and Plant Growth

A central theme in climate change botany concerns the response of plant growth to rising atmospheric carbon dioxide. As the primary substrate for photosynthesis, elevated CO₂ can stimulate carbon assimilation and improve water-use efficiency by reducing stomatal conductance, a phenomenon collectively termed the CO₂ fertilization effect. Experimental evidence from free-air carbon dioxide enrichment platforms has demonstrated that many species, particularly those using the C₃ photosynthetic pathway, increase biomass production under elevated CO₂ (Walker et al., 2021). However, the magnitude and persistence of this stimulation are highly variable and frequently constrained by other factors. Nutrient availability, especially nitrogen and phosphorus, often limits the capacity of plants to convert additional photosynthate into sustained growth, leading to progressive nitrogen limitation over time (Terrer et al., 2019).

Warming exerts its own complex influence on growth. Moderate temperature increases can extend growing seasons and accelerate metabolic processes in temperate and boreal systems, potentially enhancing productivity (Zhu et al., 2016). Yet beyond species-specific thermal optima, elevated temperatures impose stress, increase respiratory carbon losses, and exacerbate water demand through heightened evapotranspiration, with the balance between photosynthesis, photorespiration, and respiration ultimately determining the net carbon outcome (Dusenge et al., 2019). The interaction between warming and water availability is particularly consequential: in many regions, warming-induced drought stress offsets or reverses the potential benefits of a longer growing season (Yuan et al., 2019). The net effect on growth therefore depends on the regional balance between thermal and hydrological constraints, producing geographically divergent outcomes.

Beyond aboveground biomass, climate change reshapes patterns of carbon allocation between roots, stems, and leaves, as well as belowground interactions with soil microbial communities. Plants experiencing water limitation frequently allocate proportionally more carbon to root systems to enhance water acquisition, altering ecosystem carbon storage dynamics. Mycorrhizal associations mediate much of the response to elevated CO₂ and nutrient limitation, with the type of symbiosis influencing whether plants can sustain growth stimulation (Terrer et al., 2016). These belowground processes remain comparatively understudied yet are pivotal to predicting how terrestrial carbon sinks will evolve under continued climatic change.

2.2 Phenological Shifts and Ecological Mismatches

Among the most robustly documented signatures of climate change is the alteration of plant phenology. Across temperate and boreal regions, spring events such as budburst, leaf unfolding, and flowering have advanced substantially as warming brings forward the accumulation of



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thermal energy required to trigger development. Long-term observational networks and satellite-derived indices consistently reveal earlier onset of the growing season over recent decades (Piao et al., 2019). Autumn phenology, by contrast, exhibits weaker and more variable trends, with leaf senescence delayed in some systems and advanced in others, reflecting the complex interplay of temperature, photoperiod, and water stress in governing the end of season.

The ecological significance of phenological change lies not only in the shifts themselves but in their potential to generate mismatches between interacting species. Plants and their pollinators, herbivores, and seed dispersers have historically maintained synchronized life cycles, yet differential sensitivity to climatic cues can decouple these relationships. When flowering advances faster than the emergence of pollinating insects, reproductive success may decline, with consequences for both plant and animal populations (Renner & Zohner, 2018). Such trophic asynchrony represents a subtle but potentially far-reaching mechanism by which climate change erodes the integrity of ecological networks, and the degree to which species can track shifting conditions carries measurable demographic consequences for plant populations (Cleland et al., 2024).

Phenological responses are further complicated by the role of chilling requirements and photoperiod. Many temperate species require a period of winter cold to break dormancy before warmth can drive spring development. As winters warm, insufficient chilling may delay or destabilize budburst, partially counteracting the advancing effect of spring warmth (Fu et al., 2015). Photoperiodic constraints similarly limit the degree to which some species can track warming, since day length remains fixed regardless of temperature. These regulatory safeguards introduce nonlinearity into phenological responses and caution against extrapolating simple temperature-driven advances into the future.

2.3 Biodiversity, Range Shifts, and Community Reorganization

Climate change is reshaping the geography of plant life as species track their preferred climatic conditions across space. A widely observed response is the movement of species toward higher latitudes and elevations as warming renders previously suitable habitats inhospitable and opens new territory at cooler margins (Lenoir et al., 2020). Mountain systems provide especially clear evidence of upslope migration, with alpine plant communities accumulating species from lower elevations in a process sometimes described as thermophilization, and the resulting acceleration in summit species richness has been directly linked to warming (Steinbauer et al., 2018). However, the capacity of species to migrate is constrained by dispersal ability, habitat fragmentation, and the velocity of climate change, which in many landscapes outpaces the rate at which plants can relocate.

Where migration cannot keep pace with shifting climate, populations may decline or disappear, contributing to local extinctions and the contraction of species ranges. Species occupying narrow



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climatic niches, restricted geographic ranges, or specialized habitats are particularly vulnerable (Trew & Maclean, 2021). The differential ability of species to respond produces winners and losers, reshuffling community composition and frequently favoring generalist, thermophilic, and competitively dominant species at the expense of specialists. Such reorganization can homogenize biotas across regions, eroding the distinctiveness of local floras and diminishing beta diversity.

The consequences of these shifts extend to ecosystem function. Changes in species composition alter the distribution of functional traits within communities, influencing productivity, nutrient cycling, and resilience to disturbance (Bjorkman et al., 2018). The loss or decline of functionally important species can disproportionately affect ecosystem processes, while the arrival of novel species may introduce unfamiliar interactions. Importantly, climate-driven biodiversity change does not occur in isolation but compounds with land-use change, invasive species, and other anthropogenic pressures, frequently producing synergistic effects that exceed the impact of any single driver. In some ecotones, these pressures culminate in abrupt regime shifts, as documented where warming has driven the expansion of mangroves into salt marsh systems (Cavanaugh et al., 2019).

2.4 Extreme Events and Multi-Stressor Interactions

While gradual shifts in mean climate exert pervasive influence, the increasing frequency and severity of extreme events impose acute and sometimes catastrophic stresses on plant systems. Heatwaves, droughts, and their co-occurrence can overwhelm physiological tolerances, triggering hydraulic failure, carbon starvation, and widespread mortality. Episodes of drought-induced tree die-off have been documented across forest biomes worldwide, raising concerns about the stability of major carbon sinks (Hartmann et al., 2018). Such mortality events can transform ecosystems abruptly, shifting forests toward shrublands or grasslands and releasing stored carbon to the atmosphere, thereby threatening the climate mitigation potential that forests are often expected to provide (Anderegg et al., 2020).

The combination of multiple stressors frequently produces effects that cannot be predicted from single-factor studies. Elevated temperature amplifies the impact of drought, while nutrient limitation modulates the response to elevated CO₂, and the timing of stress relative to developmental stage determines its severity. A growing recognition of these interactions has prompted calls for experimental designs that manipulate several climatic drivers simultaneously, since the prevailing reliance on single-factor manipulations risks both overestimating and underestimating real-world responses (Song et al., 2019). Compound and sequential extremes, such as a drought followed by a heatwave, may be especially damaging because they erode the recovery capacity of vegetation.



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Plant responses to multi-stressor environments are further shaped by phenotypic plasticity and the potential for evolutionary adaptation. Some populations harbor sufficient genetic variation to adapt to changing conditions across generations, while others rely on plastic adjustments within the lifespan of individuals. The relative contributions of plasticity and adaptation, and whether they will prove sufficient to keep pace with the rate of climatic change, remain among the most pressing open questions in the field (Nicotra et al., 2015). Understanding the limits of plant resilience is critical for anticipating which systems are most at risk and where intervention may be required.

3. CONCLUSION

The evidence synthesized in this review makes clear that climate change is exerting profound, multifaceted, and accelerating effects on terrestrial plant systems. Rising atmospheric carbon dioxide can stimulate photosynthesis and growth, but these gains are routinely tempered by nutrient limitation, water stress, and physiological acclimation, rendering the CO₂ fertilization effect far less universal and durable than early optimism suggested. Warming temperatures lengthen growing seasons in some regions while imposing lethal stress in others, producing a geographically heterogeneous mosaic of growth responses governed by the local balance of thermal and hydrological constraints.

Phenological shifts represent one of the clearest fingerprints of climate change, with spring events advancing across much of the temperate and boreal world. Yet the ecological significance of these shifts lies less in their occurrence than in the mismatches they generate, as differential species sensitivities decouple the synchronized interactions that sustain ecological networks. The regulatory roles of chilling and photoperiod introduce important nonlinearities, reminding us that phenological futures cannot be reliably extrapolated from temperature trends alone.

At the level of biodiversity, climate change is redrawing the distribution of plant life, driving poleward and upslope migrations, precipitating local extinctions among vulnerable specialists, and reorganizing communities in ways that frequently favor generalists and homogenize regional floras. These compositional changes reverberate through ecosystem function, altering productivity, nutrient cycling, and resilience, and they interact synergistically with other anthropogenic pressures. The intensification of extreme events adds an acute dimension of risk, capable of transforming ecosystems abruptly and undermining the very carbon sinks upon which climate stabilization depends.

Taken together, these findings underscore that plant responses to climate change are characterized by complexity, context-dependence, and considerable uncertainty. They are neither uniformly negative nor reassuringly benign, but contingent on the interplay of multiple drivers, the traits and adaptive capacities of individual species, and the spatial and temporal scales of observation. A nuanced appreciation of this heterogeneity is essential for credible forecasting



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and for the design of conservation and management strategies capable of sustaining biodiversity and ecosystem services in a rapidly changing world.

4. FUTURE WORK

Despite considerable progress, important gaps persist that constrain our ability to predict the trajectory of plant systems under continued climatic change. A foremost priority is the wider adoption of multi-factor experimental designs that manipulate temperature, carbon dioxide, water, and nutrients simultaneously. The historical reliance on single-factor manipulations, while analytically tractable, fails to capture the interactive and often non-additive responses that dominate real-world conditions. Future experiments should also extend over longer durations to capture acclimation, adaptation, and the legacy effects of extreme events, which short-term studies cannot reveal.

A second priority is the improved representation of belowground processes, including root dynamics, soil microbial communities, and mycorrhizal symbioses, which mediate much of the plant response to climate yet remain disproportionately understudied. Integrating belowground carbon and nutrient dynamics into ecosystem models is essential for accurate projections of terrestrial carbon storage. Closely related is the need to incorporate intraspecific variation and evolutionary processes into predictive frameworks, since the capacity for plasticity and adaptation will substantially shape which populations persist and which decline.

Third, the field would benefit from predictive frameworks that explicitly couple physiological, phenological, and population-level responses rather than treating them in isolation. Linking mechanistic understanding across these scales would enable more reliable forecasts of how individual responses propagate to community reorganization and ecosystem function. Advances in remote sensing, high-throughput phenotyping, and machine learning offer powerful tools to bridge scales and to detect emerging patterns across the heterogeneous landscapes in which plants actually grow.

Finally, future research must broaden its geographic and taxonomic scope. Much of the existing evidence derives from temperate and boreal systems and from a limited set of model species, leaving tropical ecosystems, arid biomes, and the vast majority of plant diversity comparatively neglected. Expanding observational networks and experimental infrastructure in underrepresented regions, while strengthening collaboration across disciplines and borders, will be vital for developing a truly global understanding. Pursuing these directions will sharpen the mechanistic insight needed to anticipate ecosystem change and to inform the adaptive conservation strategies upon which the resilience of both biodiversity and human societies increasingly depends.



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