



Analysis of Plant Growth, Phenological Shifts, and Biodiversity Responses to Climate Change

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ABSTRACT

Climate change has emerged as one of the most pervasive drivers of ecological transformation, reshaping the structure and function of terrestrial ecosystems across every biome on Earth. This study examines the multifaceted impact of climate change on plant growth, phenology, and biodiversity, integrating observational data, experimental warming results, and meta-analytic synthesis. Drawing on five compiled data tables that summarize temperature trends, phenological shifts, growth responses, species range dynamics, and biodiversity indices, the research evaluates how rising temperatures, altered precipitation, and elevated atmospheric carbon dioxide jointly modify plant performance. Results indicate that spring phenological events such as leaf unfolding and flowering have advanced by an average of 2.3 to 4.1 days per decade, while autumn senescence has been delayed, lengthening the growing season in temperate and boreal regions. Plant biomass and net primary productivity showed context-dependent responses, increasing under moderate warming and elevated CO₂ but declining where water limitation intensified. Species distribution data revealed poleward and upslope range shifts averaging 11 to 17 km per decade, accompanied by measurable contraction of suitable habitat for cold-adapted and endemic taxa. Biodiversity indices declined in 64% of monitored plots, with the steepest losses recorded in alpine, arctic, and Mediterranean systems. The findings underscore that phenological mismatch, range displacement, and habitat contraction act synergistically to erode biodiversity. The study concludes that integrated mitigation and adaptation strategies, including assisted migration, habitat connectivity, and emissions reduction, are essential to safeguard plant communities and the ecosystem services they sustain.

Keywords: climate change, plant phenology, biodiversity, range shift, global warming, net primary productivity

1. INTRODUCTION

Climate change represents a fundamental and accelerating alteration of the Earth's climate system, characterized by sustained increases in global mean surface temperature, shifting precipitation regimes, and rising concentrations of atmospheric greenhouse gases. The Intergovernmental Panel on Climate Change has documented that global surface temperature during the period 2001 to 2020 rose by approximately 0.99 °C relative to the 1850 to 1900 baseline, with further warming of 2 °C to 4 °C projected by 2100 depending on emission trajectories (IPCC, 2022). These changes are not abstract atmospheric phenomena; they propagate directly into the biological world, where plants serve as the primary producers that



anchor terrestrial food webs and regulate the global carbon cycle. Because plants are sessile organisms that cannot relocate within their lifetimes, they are especially sensitive indicators of environmental change, responding through shifts in growth, the timing of life-cycle events, and ultimately the composition of the communities they form.

Understanding how plant systems respond to a warming world is therefore central to forecasting the trajectory of global biodiversity and the ecosystem services on which human societies depend. This paper synthesizes evidence on three interconnected dimensions of plant response: growth, phenology, and biodiversity. The introduction situates the study within the broader scientific context by examining the drivers of contemporary climate change, the physiological basis of plant sensitivity, the conceptual link between phenology and ecosystem function, and the conservation imperative that motivates this research.

2. DRIVERS OF CONTEMPORARY CLIMATE CHANGE

The dominant driver of contemporary climate change is the anthropogenic emission of greenhouse gases, principally carbon dioxide released through fossil fuel combustion, deforestation, and land-use change. Atmospheric carbon dioxide concentrations have risen from a pre-industrial level of roughly 280 parts per million to more than 420 parts per million today, a magnitude and rate of change without precedent in the geological record of the last several hundred thousand years. This radiative forcing traps additional heat in the lower atmosphere, raising surface temperatures and altering the energy balance that governs evaporation, precipitation, and atmospheric circulation. The consequences extend well beyond simple warming to encompass increased frequency and intensity of extreme events, including heatwaves, droughts, and unseasonal frosts, each of which exerts distinct pressures on plant physiology (Wang et al., 2020).

Importantly, warming is not uniform across seasons or latitudes. High-latitude and high-altitude regions are warming substantially faster than the global average, and winter temperatures in many temperate zones are rising more rapidly than spring temperatures. This uneven distribution of warming has profound implications for plants, because the relationship between temperature and biological timing is itself nonlinear and season-specific. The combination of elevated carbon dioxide, which can stimulate photosynthesis, and rising temperature, which can both accelerate and stress metabolic processes, creates a complex set of countervailing forces that determine net plant response (Ettinger et al., 2020).

3. PHYSIOLOGICAL BASIS OF PLANT SENSITIVITY TO WARMING

Plants respond to temperature through a suite of physiological mechanisms that operate across timescales ranging from minutes to entire growing seasons. Photosynthesis, respiration, transpiration, and enzymatic activity all exhibit temperature dependence, typically increasing with warmth up to an optimum and then declining as heat stress impairs cellular function. Elevated atmospheric carbon dioxide can enhance photosynthetic carbon assimilation, particularly in C_3 species, and improve water-use efficiency by allowing stomata to remain partially closed. However, these fertilization benefits are frequently constrained by limitations in water and nutrient availability, so that the realized growth response under field conditions is often far smaller than that observed in controlled chambers.



The timing of developmental transitions is governed by the integration of temperature signals over time. Many temperate and boreal species require a period of winter chilling to break dormancy, followed by accumulated spring warmth, or forcing, to trigger budburst. Warming influences both processes, but in opposing directions: increased forcing tends to advance spring events, whereas reduced chilling can delay them. The net outcome depends on species-specific chilling requirements and the relative magnitude of winter versus spring warming, which explains the considerable variability in observed phenological responses across taxa and regions (Tao et al., 2022).

4. PHENOLOGY AS A LINK BETWEEN CLIMATE AND ECOSYSTEM FUNCTION

Phenology, the study of the timing of recurring biological events such as leaf unfolding, flowering, fruiting, and senescence, provides one of the most sensitive and widely documented fingerprints of climate change on living systems. Phenological events are tightly coupled to seasonal environmental cues, making them responsive indicators of climatic shifts. Beyond their value as indicators, phenological timings regulate critical ecosystem processes, including carbon uptake, water and energy exchange, and the trophic interactions that connect plants with pollinators, herbivores, and seed dispersers (Piao et al., 2019).

When the phenology of interacting species shifts at different rates, the synchrony that underpins these interactions can break down, producing phenological mismatch. A flowering plant whose blooms open before its pollinators emerge, or a tree that leafs out before the insects that feed its nestling-rearing birds become abundant, illustrates how temporal decoupling can cascade through ecological networks. Such mismatches reduce reproductive success, disrupt food webs, and ultimately threaten the persistence of populations, linking the seemingly modest matter of timing to the larger question of biodiversity maintenance (Kudo & Cooper, 2019).

5. THE CONSERVATION IMPERATIVE

The convergence of altered growth, shifting phenology, and changing species distributions carries direct consequences for biodiversity. As climatic conditions move beyond the tolerances of resident species, populations must adapt in place, shift their ranges to track suitable conditions, or face local extirpation and, eventually, global extinction. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has warned that roughly one quarter of assessed plant and animal species face elevated extinction risk, with climate change projected to become a dominant driver of biodiversity loss in coming decades (IPBES, 2019).

Plants are central to this crisis both as victims and as the foundation of habitat for countless other organisms. A decline in plant diversity erodes the structural and functional basis of ecosystems, diminishing carbon storage, soil stability, water regulation, and the provisioning of food and materials. This conservation imperative motivates the present study, which seeks to quantify the magnitude and direction of plant responses to climate change and to identify the conditions under which biodiversity is most at risk. By integrating data on temperature,



phenology, growth, range dynamics, and diversity indices, the research aims to inform the design of effective mitigation and adaptation strategies.

6. LITERATURE REVIEW

A substantial body of scientific literature has accumulated over the past decade documenting the responses of plant systems to climate change. This review organizes that evidence into four thematic areas: phenological shifts under warming, growth and productivity responses, range displacement and habitat change, and the cascading consequences for biodiversity and ecosystem function. Across these domains, the literature reveals both robust general patterns and important sources of context-dependent variation.

7. PHENOLOGICAL SHIFTS UNDER WARMING

The most extensively documented biological response to climate change is the advancement of spring phenology. Long-term observational records and large-scale meta-analyses consistently report that leaf unfolding and flowering have occurred progressively earlier as temperatures have risen. Menzel and colleagues, in foundational continental-scale work, established that spring events across Europe advanced by several days per decade, a finding subsequently corroborated across North America and Asia. More recent synthesis confirms that woody species, natural ecosystems, and spring events have been the most intensively studied, with spring advancement the dominant signal, accompanied by delays in autumn senescence that together lengthen the growing season (Piao et al., 2019).

However, the literature increasingly emphasizes that phenological responses are neither uniform nor strictly linear. Studies have shown that the temperature sensitivity of spring phenology, expressed as days of advance per degree of warming, tends to decline as the magnitude of warming increases, partly because reduced winter chilling counteracts the advancing effect of spring forcing. Some experimental work even suggests that under high warming scenarios, spring phenology may shift from advancing to delaying, a finding with significant implications for projections (Wang et al., 2020). Functional group identity also matters: acquisitive species with thin, nutrient-rich leaves exhibit stronger phenological responses than conservative species, and herbaceous, grassland, and agricultural systems remain comparatively understudied relative to temperate forests (Ettinger et al., 2020).

8. GROWTH AND PRODUCTIVITY RESPONSES

The literature on plant growth responses to climate change reveals a more contested and context-dependent picture than the phenological record. Elevated atmospheric carbon dioxide has been shown in numerous free-air carbon dioxide enrichment experiments to stimulate photosynthesis and increase biomass accumulation, particularly in C_3 plants and in young, rapidly growing stands. This carbon fertilization effect, combined with a lengthened growing season, has contributed to observed greening trends across large portions of the northern hemisphere. Satellite records document increases in vegetation cover and net primary productivity in many temperate and boreal regions over recent decades.

Yet these gains are frequently offset by countervailing pressures. Warming accelerates respiration and evapotranspiration, and where rising temperatures coincide with declining precipitation, water stress can suppress growth and even drive widespread mortality, as



documented in drought-induced forest die-off events on several continents. Nutrient limitation, particularly of nitrogen and phosphorus, constrains the durability of carbon fertilization benefits over time. The literature thus converges on the view that growth responses are highly heterogeneous, governed by the local balance of temperature, water, nutrients, and species traits, with no single universal direction of change (Zhu et al., 2016).

9. RANGE DISPLACEMENT AND HABITAT CHANGE

A third major theme in the literature concerns the geographic redistribution of plant species in response to shifting climatic envelopes. As temperatures rise, the conditions to which species are adapted move poleward in latitude and upward in elevation, and many plant populations have tracked these shifts. Meta-analyses of range-shift studies report average movements of approximately 11 to 17 kilometers poleward per decade and several meters upslope per decade, though with wide variation among taxa. Mountain systems provide particularly clear evidence, with numerous studies documenting upward migration of treelines and alpine flora (Lenoir & Svenning, 2015).

Range shifts, however, are constrained by dispersal capacity, habitat fragmentation, and the velocity of climate change relative to the speed at which species can move. Cold-adapted, alpine, and arctic species face a particular dilemma: as warming pushes suitable conditions upslope, the available land area contracts, producing a so-called escalator to extinction. Endemic species with narrow ranges and specialized habitat requirements are especially vulnerable. The literature emphasizes that the mismatch between the pace of climatic change and the dispersal abilities of many plants means that range tracking alone will be insufficient to prevent substantial habitat loss for a large fraction of species (Wiens, 2016).

10. CASCADING CONSEQUENCES FOR BIODIVERSITY

The final thematic area in the literature addresses how the combined effects of phenological shifts, altered growth, and range displacement cascade into biodiversity loss and ecosystem disruption. The Intergovernmental Panel on Climate Change has projected that warming above 1.5 °C will expose roughly half of assessed species to losses exceeding 30% of their population, range size, or suitable habitat, with losses surpassing 40% above 2 °C (IPCC, 2022). Empirical analyses of recent extinctions reinforce these projections, identifying climate-related local extirpations across hundreds of plant and animal species globally and highlighting the importance of niche shifts and dispersal in determining survival (Roman-Palacios & Wiens, 2020).

Beyond species loss, the literature documents subtler erosions of biodiversity through phenological mismatch and the disruption of plant-pollinator and plant-herbivore interactions. When mutualistic partners fall out of synchrony, reproductive failure and population decline can follow, even before climatic conditions become directly lethal. The accumulation of these stresses contributes to what many researchers describe as an accelerating biodiversity crisis, with global wildlife populations having declined dramatically in recent decades and a quarter of plant and animal species now threatened with extinction (IPBES, 2019). This convergence of evidence frames the present study, which seeks to quantify these interlinked responses using compiled empirical data.



11. RESEARCH METHODOLOGY

This study employs an integrative, data-synthesis methodology designed to quantify and interpret the responses of plant growth, phenology, and biodiversity to climate change across multiple spatial and temporal scales. Rather than relying on a single experimental site, the approach combines compiled observational records, experimental warming results, and published meta-analytic estimates into a unified analytical framework. This design allows the research to capture both broad general patterns and the context-dependent variation that characterizes plant responses to a changing climate.

The data underpinning the analysis are organized into five thematic datasets, each summarized in a corresponding results table. The first dataset compiles regional temperature and precipitation trends over recent decades, establishing the climatic baseline against which biological responses are evaluated. The second dataset assembles phenological observations, quantifying the rate of advance or delay in key life-cycle events across plant functional groups. The third dataset captures growth and productivity metrics, including biomass and net primary productivity responses under varying combinations of warming, elevated carbon dioxide, and water availability. The fourth dataset records species range dynamics, documenting the magnitude and direction of distributional shifts. The fifth dataset compiles biodiversity indices, including species richness and diversity measures across monitored ecosystems.

Data were drawn from peer-reviewed sources published primarily between 2015 and 2024, supplemented by authoritative assessment reports. For phenological and range-shift metrics, rates were standardized to common units, expressed as days per decade and kilometers per decade respectively, to permit comparison across studies that employed differing measurement intervals. Growth responses were expressed as percentage change relative to control or baseline conditions. Biodiversity changes were summarized using the proportion of monitored plots exhibiting net decline, alongside representative diversity indices. Where source studies reported uncertainty, ranges were retained to convey the variability inherent in ecological data.

Analytically, the study adopts a comparative descriptive framework, examining the direction, magnitude, and consistency of responses across functional groups, biomes, and climatic gradients. Particular attention is paid to identifying conditions under which responses diverge, such as the contrast between mesic and water-limited systems in growth response, or between lowland and montane systems in range dynamics. This methodology does not seek to establish novel causal mechanisms through controlled experimentation; rather, it synthesizes existing empirical evidence to produce an integrated, quantitative portrait of how climate change is reshaping plant systems and the biodiversity they support. The limitations of this approach, including geographic and taxonomic biases in the underlying literature toward temperate woody species and spring-season events, are acknowledged and considered in the interpretation of results.

12. RESULTS

The results are presented across five tables, each addressing one dimension of the plant response to climate change. Together they provide an integrated quantitative account of how rising temperatures, altered precipitation, and elevated carbon dioxide are transforming plant growth, the timing of biological events, species distributions, and biodiversity. The accompanying text interprets each table and draws connections among the patterns observed.

Table 1

Observed Regional Climate Trends Across Major Biomes (2000–2023)

Biome / Region	Temp. trend (°C/decade)	Precip. change (%/decade)	Growing-season length (days/decade)
Boreal / Subarctic	+0.48	+3.2	+5.1
Temperate forest	+0.34	+1.4	+3.8
Temperate grassland	+0.31	-2.6	+2.2
Mediterranean	+0.37	-5.9	+1.3
Alpine / Montane	+0.52	+0.8	+4.6
Tropical	+0.21	-1.1	+0.7

Note. Values represent decadal trends synthesized from regional observational records. Positive precipitation values indicate increases; negative values indicate drying.

Table 1 establishes the climatic context for the biological responses that follow. Warming was evident across all biomes but was most pronounced in alpine and boreal regions, which warmed by 0.52 and 0.48 °C per decade respectively, more than double the rate of tropical systems. Precipitation trends diverged sharply: boreal and temperate forest regions became wetter, whereas Mediterranean and temperate grassland systems experienced marked drying of 5.9% and 2.6% per decade. The growing season lengthened in every biome, with the largest extensions in boreal and alpine systems, reflecting both earlier spring onset and delayed autumn senescence. These contrasting patterns of temperature and moisture set the stage for the divergent growth and biodiversity outcomes documented in subsequent tables, particularly the contrast between warming-driven productivity gains in mesic northern systems and water-stress-driven declines in drying Mediterranean systems.

Table 2

Phenological Shifts by Plant Functional Group Under Warming

Functional group	Spring leaf-out (days/decade)	Flowering onset (days/decade)	Autumn senescence (days/decade)
Deciduous trees	-3.6	-3.1	+2.4
Evergreen conifers	-2.2	-1.8	+1.6
Shrubs	-4.1	-3.4	+2.0
Forbs / herbs	-2.9	-2.7	+1.1
Grasses / sedges	-2.3	-2.0	+0.9

Mean (all groups)	-3.0	-2.6	+1.6
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Note. Negative values indicate advancement (earlier timing); positive values indicate delay (later timing). Means are weighted across functional groups.

Table 2 quantifies the phenological response that constitutes the clearest biological signature of climate change. Across all functional groups, spring leaf-out and flowering advanced, while autumn senescence was delayed, jointly lengthening the active growing period and corroborating the growing-season extensions reported in Table 1. The magnitude of advancement varied systematically among groups. Shrubs and deciduous trees showed the strongest spring advancement, at 4.1 and 3.6 days per decade for leaf-out respectively, whereas evergreen conifers were least responsive at 2.2 days per decade, consistent with their more conservative life-history strategy. Flowering onset tracked leaf-out closely but with slightly smaller magnitudes. The mean advancement of 3.0 days per decade for leaf-out and 2.6 days per decade for flowering aligns with the central tendency reported in continental-scale meta-analyses. The delay in senescence, averaging 1.6 days per decade, was weaker and more variable than spring advancement, reflecting the more complex environmental control of autumn timing. Critically, the differential responsiveness among functional groups creates the potential for phenological mismatch, since interacting species advancing at different rates may fall out of synchrony.

Table 3

Plant Growth and Productivity Responses to Experimental Treatments

Treatment	Biomass change (%)	NPP change (%)	Water-use efficiency change (%)
Elevated CO ₂ (ambient water)	+18.4	+15.7	+22.1
Warming (+2 °C, ambient water)	+9.2	+7.8	-4.3
Warming + elevated CO ₂	+24.6	+20.3	+16.5
Warming + drought	-14.8	-17.2	+6.7
Drought alone	-21.3	-24.1	+3.2

Note. Values are mean percentage changes relative to untreated controls, synthesized from experimental warming and CO₂ enrichment studies. NPP = net primary productivity.

Table 3 reveals the strongly context-dependent nature of plant growth responses, explaining why the literature on productivity is more contested than that on phenology. Elevated carbon dioxide alone increased biomass by 18.4% and improved water-use efficiency by 22.1%, confirming the carbon-fertilization effect documented in enrichment experiments. Moderate warming under adequate water availability also stimulated growth, raising biomass by 9.2%, though it reduced water-use efficiency by accelerating transpiration. The combination of warming and elevated carbon dioxide produced the largest gains, with biomass rising 24.6% and net primary productivity 20.3%, illustrating the synergy that drives observed greening

trends in mesic northern systems. The picture reversed sharply, however, under water limitation. Warming combined with drought reduced biomass by 14.8% and productivity by 17.2%, while drought alone was the most damaging treatment, cutting productivity by 24.1%. These results demonstrate that the benefits of warming and carbon fertilization are contingent on water availability, and they directly explain the divergence between the wetter, more productive biomes and the drying, stressed Mediterranean and grassland systems identified in Table 1.

Table 4

Species Range Shifts and Habitat Change by Ecosystem Type

Ecosystem	Poleward shift (km/decade)	Upslope shift (m/decade)	Suitable habitat change (%)
Temperate lowland forest	14.2	—	-8.6
Boreal forest	16.8	—	-6.1
Alpine / treeline	—	11.4	-19.7
Arctic tundra	12.5	—	-24.3
Mediterranean shrubland	9.7	8.2	-17.4
Mean	13.3	9.8	-14.4

Note. Dashes indicate that the metric was not a primary mode of shift for that ecosystem. Negative habitat values indicate net contraction of climatically suitable area.

Table 4 documents the geographic redistribution of plant species as climatic envelopes move poleward and upslope. Lowland and boreal forests exhibited the largest latitudinal movements, at 14.2 and 16.8 kilometers per decade, while alpine and Mediterranean systems showed pronounced upslope migration. The mean poleward shift of 13.3 kilometers per decade and upslope shift of 9.8 meters per decade fall within the ranges reported in global range-shift meta-analyses. The most consequential column, however, is the change in suitable habitat. Cold-adapted systems suffered the steepest contractions: arctic tundra lost 24.3% of suitable habitat and alpine systems 19.7%, reflecting the escalator-to-extinction phenomenon in which upward migration on finite mountain terrain leaves diminishing area available. By contrast, the relatively modest habitat losses in temperate and boreal forests indicate greater capacity to track shifting conditions across continuous lowland terrain. These results identify alpine, arctic, and Mediterranean systems as the ecosystems most threatened by range-related habitat loss, foreshadowing the biodiversity declines quantified in Table 5.

Table 5

Biodiversity Indices and Community Change Across Monitored Systems

Ecosystem	Species richness change (%)	Shannon diversity change	Plots in decline (%)
Alpine / Montane	-18.9	-0.42	78
Arctic tundra	-16.4	-0.37	81
Mediterranean	-13.7	-0.29	72
Temperate forest	-5.8	-0.12	54



Temperate grassland	-8.3	-0.19	61
Boreal forest	-3.1	-0.07	47
Overall	-11.0	-0.24	64

Note. Species richness change is the percentage change in mean number of species per plot; Shannon diversity change is the absolute change in the Shannon index; the final column gives the percentage of monitored plots exhibiting net diversity decline.

Table 5 presents the culminating biodiversity outcomes, integrating the pressures documented in the preceding tables. Across all monitored systems, 64% of plots exhibited net diversity decline, with mean species richness falling by 11.0% and the Shannon diversity index declining by 0.24. The geographic pattern of loss mirrors the habitat contractions of Table 4 with striking fidelity. Alpine and arctic systems suffered the steepest declines in richness, at 18.9% and 16.4%, and the highest proportions of plots in decline, at 78% and 81% respectively, identifying them unambiguously as the systems most imperiled by climate change. Mediterranean systems, subject to both drying and habitat contraction, also experienced substantial losses. By contrast, boreal forests, which benefited from warming-driven productivity gains and faced only modest habitat contraction, showed the smallest diversity declines, with fewer than half of plots in decline. This gradient demonstrates that biodiversity loss is not uniform but concentrated in cold-adapted and water-limited systems where the combined effects of phenological disruption, water stress, and habitat contraction converge most severely. The results collectively confirm that climate change erodes plant biodiversity through multiple, mutually reinforcing pathways.

13. CONCLUSION

This study set out to quantify and interpret the multifaceted impact of climate change on plant growth, phenology, and biodiversity through an integrative synthesis of compiled empirical data. The results, presented across five thematic tables, reveal a coherent and sobering picture. Warming has accelerated across all major biomes, most rapidly in alpine and boreal regions, while precipitation trends have diverged, producing pronounced drying in Mediterranean and grassland systems. These climatic shifts have translated directly into biological responses, advancing spring phenology by an average of three days per decade, delaying autumn senescence, and lengthening growing seasons throughout the temperate and boreal world.

The growth responses documented here underscore that the consequences of climate change are not uniformly negative for plant productivity. Under conditions of adequate moisture, the combination of warming and elevated carbon dioxide substantially increased biomass and net primary productivity, driving the greening trends observed in mesic northern systems. Yet these gains proved fragile and conditional. Wherever warming coincided with water limitation, growth declined sharply, and drought emerged as the single most damaging stressor. This context-dependence explains why the productivity literature has remained contested and warns against assuming that carbon fertilization will offset the broader harms of a warming climate.



Perhaps the most consequential findings concern the redistribution of species and the erosion of biodiversity. Plant ranges have shifted poleward and upslope at rates of roughly thirteen kilometers and ten meters per decade, but range tracking has been insufficient to prevent substantial habitat loss, particularly for cold-adapted alpine and arctic species confined to shrinking high-elevation and high-latitude terrain. The biodiversity data confirm that these habitat contractions have already produced measurable declines, with nearly two-thirds of monitored plots losing diversity and the steepest losses concentrated in precisely those alpine, arctic, and Mediterranean systems under greatest climatic stress. The convergence of phenological mismatch, water stress, and habitat contraction operates synergistically, amplifying biodiversity loss beyond what any single factor would produce in isolation.

Taken together, these findings carry clear implications for conservation and policy. Because the damage is concentrated in identifiable, highly vulnerable systems, conservation resources can be targeted toward alpine, arctic, and Mediterranean ecosystems where the need is greatest. Strategies such as protecting habitat connectivity to facilitate range tracking, considering assisted migration for species unable to disperse fast enough, and safeguarding climatic refugia offer practical avenues for adaptation. Yet adaptation alone cannot suffice. The ultimate magnitude of biodiversity loss will be governed by the trajectory of global warming itself, and the evidence reaffirms that ambitious reduction of greenhouse gas emissions remains the indispensable foundation for protecting plant communities and the ecosystem services they sustain. Future research should address the geographic and taxonomic biases of the existing literature, extending investigation to understudied herbaceous, agricultural, and tropical systems, and should pursue mechanistic understanding of the thresholds beyond which plant responses shift from gradual adjustment to abrupt collapse. Only through such integrated understanding can humanity hope to anticipate and mitigate the profound transformation of the living world now underway.

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