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# *Impact of Climate Change on Plant Growth*

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***Abstract.*** Climate change creates challenges to plant ecosystems worldwide by altering global temperature and atmospheric $CO_2$ concentrations. This study investigates how climate change influences seagrass metabolism, temperate phenology, and developmental traits across diverse taxa. Drawing on published temperature-response curves for Zostera marina, long-term phenological datasets for temperate trees, and controlled experiments on $CO_2$ enrichment. This essay synthesizes findings on metabolic balance, seasonal timing, and morphological adjustments. Results indicate that rising water temperatures reduce the photosynthesis-to-respiration ratio in eelgrass, thereby constraining growth; 72% of temperate species show significant spring phenological advancement at a rate of approximately one day per decade; and elevated global $CO_2$ concentration enhances leaf cell expansion, root branching, and stomata regulation via gene-mediated pathways. These responses vary with species' thermal tolerances and vernalization requirements, causing heterogeneous shifts in distribution and productivity. This essay highlights that multifactorial interactions—temperature, $CO_2$ and water availability—must be integrated to forecast plant resilience accurately. By bridging ecophysiological experiments with regional modeling, this work highlights critical knowledge gaps in phenological drivers. These insights advance the ability to anticipate climate-driven vegetation changes and inform adaptive conservation strategies.

***Keywords:*** Plant, Climate change, Plant development, Plant morphology.

## 1. Introduction

Over the past two centuries, human activities like cutting trees and the burning of fossil fuels have raised atmospheric $CO_2$ concentration from roughly 280 ppm in the pre-industrial era to over 415 ppm today, with predictions reaching 730–1,000 ppm by the end of the twenty-first century under a high pollution environment [1,2]. Average global surface temperature has increased by approximately 1°C since 1880, while ocean temperatures have warmed by nearly 0.7°C, altering thermal patterns in both terrestrial and marine environments [3,4]. These changes in temperature, precipitation patterns, and $CO_2$ concentrations affect plant processes like distribution, morphology and plant development. Consequently, understanding how diverse plant taxa respond to different changing factors is essential. Laboratory and field studies on Zostera marina demonstrate that rising water temperatures disproportionately increase respiration relative to photosynthesis, causing a decline in the photosynthesis-to-respiration ratio and constraining growth [5]. Meta-analyses across multiple seagrass species predict up to 30 % range contraction under a +2–4°C increase in temperature [6]. Regional experiments in Chinese coastal meadows corroborate species-specific thermal optima and highlight the need for local adaptation strategies. Long-term records in Europe and North America reveal that nearly 72 % of temperate tree species advance spring leaf-out by about one day per decade in response to regional warming [7]. 10–18 % of species exhibit delayed or negligible shifts due to vernalization activity and photoperiod interactions [7]. In China, nationwide phenology network reports indicate plants' sensitivity to winter warming, resulting in earlier green-ups that exceed purely spring-temperature effects. Controlled-environment experiments show that elevated levels between 600 and 1,000 ppm enhance leaf cell expansion, lateral root growth and alter shoot architecture via upregulation of genes such as HIC and CRCT in both model species and crops [8]. In soybeans, higher $CO_2$ concentration combined with reduced precipitation increases root: shoot ratios and nodulation density. It also improves the water and nitrogen use efficiency [9]. Yet crop-level meta-analyses indicate that $CO_2$-driven crop yield gains may be offset by heat stress at warming above 2°C [10]. Despite extensive studies on single factors, plant responses in nature arise from simultaneous changes in temperature, $CO_2$ and water availability. Reviews that treat these factors in isolation prevent us from forecasting whole-plant and ecosystem resilience under complex climate scenarios. This essay will synthesize ecophysiological data from marine and terrestrial experiments to derive quantitative response curves for temperature rise and $CO_2$ enrichment. Meta-analyze phenological and distribution datasets to assess species-specific sensitivities, explicitly accounting for vernalization and photoperiod interactions. Develop a conceptual model linking metabolic balance, seasonal timing, and developmental adjustments under a complex model. Identify critical knowledge gaps, especially the paucity of combined-driver experiments and the need for regional model validation, and propose targeted studies using genomic and phenomic tools. By uniting empirical findings with predictive modeling, this framework aims to advance our understanding of plant adaptability in the Anthropocene, informing conservation efforts in seagrass meadows, forest management under shifting phenologies, and agricultural strategies to sustain crop productivity in a warmer, $CO_2$-rich world.

## 2. Climate change affects plants

### 2.1. Case description

Climate is causing many problems for plants around the globe, and seagrass is one of the plants affected by climate change. The average global temperature is predicted to increase by 1 ± 3.5°C by the end of the twenty-first century, which is more rapid than Earth's growth over the previous 10,000 years [5]. This increase in temperature will directly alter water temperatures in seagrass habitats, and increased water temperatures will have a direct impact on the metabolism of seagrass and the preservation of a positive carbon balance [5]. Different species with different thermal tolerance and different optimal temperatures to have metabolic reactions will have different effects with different intensities. The leaf respiration rate increases faster with higher temperature than does that of photosynthesis in eelgrass. Thus, leading to both a decrease in the photosynthesis-to-respiration ratio with higher temperature and the existence of a seasonal growth optimum[5]. However, other seagrass species with different thermal tolerance will have different reactions to the high habitat temperature. Plant growth is regulated by temperature in addition to leaf P : R influences, including root-crown ratio [5]. Some species that grow in areas with temperatures higher than their thermal tolerance limitation will decrease their productivity and distribution with increasing annual temperature.

### 2.2. Phenological shifts

The advancement of some seasons will have some effect on a plant's phenology. Alongside higher temperatures in some regions, the northern hemisphere has seen advancements in germination, bloom time, fruit and leaf growth and overall greening [7]. Further, the way plants respond to climate change is also changing with the passage of time. From 1980, the 32-year study about 13 temperate trees indicates that the "heat requirement" for leaf flushing increased by more than 50% over time. This was a startling finding, but the reason was unknown [7]. In a study, some species had no reaction or no change in timing. In some locations with higher temperatures, some even experienced delayed spring events, even if the most common response is patterns of increasing spring occurrences [7].

It is shown that 72% of species were sensitive to the higher spring temperature and responded to the warmer spring by an advanced bloom period in the year, with a blossoming advancement phase of one day per decade. 18% of those in the study were insensitive to the higher temperature, with no advance on the Phenological behaviors or even delaying the blooming period. However, by analyzing responses to different periods, the conclusion is that these species with no response were indeed sensitive to climate, but are controlled by a winter ‘vernalization’ requirement [7]. These species have their special strategies to avoid energy consumption in the midwinter and require accumulated winter chilling before responding to increasing temperatures in spring. In some species, the intense low temperature in winter advanced the spring activity, but the recent warmer winter and autumn temperature retarded the advancement of the spring activity. But as with the 72% majority, spring progress was still fueled by warmer temperatures. Only the rest 10% of the species are species that are genuinely climate insensitive.

### 2.3. Plant development

Climate change affects temperature, precipitation and $CO_2$ concentration in the atmosphere, which leads to the changing adaptation of plants in this changing environment. As a result of climate change, precipitation patterns are expected to change, with more frequent drought events predicted [2]. As atmospheric $CO_2$ concentrations approach 730–1000 ppm by the end of the century, the average global surface temperature is predicted to rise by 1.0–3.7 degrees Celsius [1,2]. These elements will affect the morphological characteristics, developmental processes, physiology and molecular function of plants [8].

#### 2.3.1. Developmental responses to high temperature

From 1880 to 2012, the higher $CO_2$ concentration and other greenhouse gases increased the average global surface temperature by about 0.85 °C [3]. Except for the increasing temperature, higher frequency, intensity, and duration of heat waves will also affect plants’ development. Thus, it is necessary for plants to make some adaptations [2]. In contrast to atmospheric $CO_2$, which is uniformly distributed globally, future projections for global surface temperature exhibit considerable variation across geographical regions, resulting in differential impacts on plants in diverse locales [8].

The molecular mechanisms by which elevated temperature changes a plant’s development are unclear. However, scientists found that height temperature will affect plant leaf development by increasing the temperature outside their optimal temperature range. In Arabidopsis, the rate of leaf initiation and when the temperature is between 6 and 26°C, expansion rises linearly, and the growth rate of new leaves will also increase as the temperature increases in this optimal temperature range [9]. If the temperature exceeds the temperature maximum, the plant will be sensitive to the temperature change and the leaf growth rate will be affected. This mechanism will also work on plant root development. The higher temperature will increase the root length within a specific range. The root growth will slow down after the temperature is out of the range. For sunflowers, 25 to 30°C is the ideal temperature range for both taproot length and lateral root [10]. In oilseed rape, the length of the taproot and the quantity of lateral roots increased as the temperature of the root development media climbed from 10 to 20°C [11]. Between 10 and 35 degrees Celsius, cotton's taproot length and lateral root number grew; however, above that point, they declined.

### 2.3.2. Developmental responses to high $CO_2$ concentration

As climate change increases the $CO_2$ concentration in the atmosphere, plants will make some adjustments to adapt to this concentration change. The increasing $CO_2$ concentration in the atmosphere may be related to the rising average leaf size in some plants. The increased cell production or higher cell expansion rate may lead to a larger average leaf area when the $CO_2$ concentration rises. These reactions vary depending on the type of cell. For example, scientists found that in the hybrid Populus × euramericana, the increased $CO_2$ concentration will only affect epidermal cells with a larger size in growing leaves but not mature leaves. However, in the spongy and palisade mesophyll cells, both young and old leaves increased their size to respond to the rising $CO_2$ concentration[12]. Additionally, they discovered that increased $CO_2$ boosted the rate of new epidermal cell formation, although this impact differed along a basipetal gradient [12]. Elevated $CO_2$ will have different effects on different types of cells [8]. Larger intercellular air gaps and an extra cell layer in the spongy mesophyll of wheat leaves occur when the $CO_2$ increases, but minimal effects on epidermal anatomy.

The higher $CO_2$ concentration will also affect plant root development. The root biomass will increase when the $CO_2$ concentration rises. The higher root: shoot ratio is also often regarded as a response from plants to high CO concentration [8]. Minirhizotron experiments in soybeans showed that increased $CO_2$ lengthens roots, particularly at shallow and intermediate soil depths, and that the density and quantity of root nodules containing the nitrogen-fixing bacteria Bradyrhizobia increase as $CO_2$ levels rise and precipitation levels fall [9]. The higher concentration of $CO_2$ will affect the water absorption efficiency of roots by changing the root system. The higher $CO_2$ concentration will lead to increased branching and expansion of lateral roots, which means the root will be prolific in the shallow layer rather than in deeper soil. This will have an impact on how root length is distributed concerning water resources.

There is a type of gene that exists in plants that responds the high $CO_2$ concentration. HIC is a type of gene in which a $CO_2$-responsive negative regulator of stomatal development is predicted to be a regulator of the stomata index for the plant cell. In the wild-type Arabidopsis accession ($C^{24}$) without out HIC gene, the response to high $CO_2$ concentration is not significant. However, in the Hic mutant type of the Arabidopsis accession, an increase in stomatal index of 18–28% suggests that the HIC gene is important to the regulation of adverse stomatal growth in reaction to increased $CO_2$ [8]. The plant will also change the shoot architecture of plants by altering the molecular mechanisms.

Scientists find a starch accumulation regulator expressed by the phloem. The over-expression of CRCT will increase the starch content and the tillering angle of plants. Thus, the plant's branches had a wider lateral spread [8].

## 3. Recommendations and contrasts

### 3.1. Current misunderstanding of climate change

There is more information on phenological fluctuations than on long-term shifts in plant distribution. Regional studies show notable interspecific diversity, despite meta-analyses showing a general poleward and upward (altitudinal) movement in plant ranges [7]. For instance, researchers looked at elevation data for 64 plant species collected during two census periods across a sizable chunk of California. They observed downward shifts in almost 72% of species, which defies basic assumptions. This underscores the importance of non-thermal climatic drivers, such as water availability, in shaping distributional dynamics [7].

Extreme climatic events further complicate predictions. Findings suggest that an extreme cold event led to a mass die-off of Scots pine (Pinus sylvestris) on the low-latitude edge of Spain, a finding that challenges models to focus only on gradual temperature changes. Similarly, the ability of alpine species to colonize areas of retreating glaciers under moderate warming suggests that biological interactions (e.g., competition) may limit range expansion more than climate suitability alone [7].

### 3.2. Future research suggestion

As mentioned above, climate change will affect several environmental factors that will affect plants in different ways. It is shown that climate change will not only affect plants by changing a single environmental factor, as the simple linear model predicted before. The $CO_2$ concentration, temperature and precipitation rate may work simultaneously to affect the plant development. Plants will also have different adaptation abilities to different changing conditions, which makes the research harder. Overall, there is still a great deal of ambiguity regarding the proportional contributions of seasonal variations in temperature, precipitation, and photoperiod to phenological dynamics. This makes it difficult for us to forecast how yearly phenological events may or may not vary in response to climatic changes [13]. Scientists need to combine methods like experiments that examine plant ecophysiological response to changes in climate change via changes in phenologies and models that establish how each phase of the life cycle responds to long-term climate trends, together to further exploration. Especially the latter one, which is the experiment that always lacks attention.

## 4. Conclusion

The results of this article indicate that climate change fundamentally alters plant function, timing, and form across ecosystems. First, elevated water temperatures disproportionately increase respiration over photosynthesis in seagrasses like Zostera marina, leading to declining carbon balance and potential range contractions. Second, long-term observations demonstrate that most temperate species advance spring phenophases by about one day per decade in response to warming, although a small number of species delay or remain unresponsive due to vernalization requirements. Third, increased atmospheric $CO_2$ stimulates leaf cell expansion, root proliferation, and shifts in shoot architecture mediated by genes such as HIC and CRCT, thereby enhancing carbon assimilation and altering biomass allocation. Collectively, these findings highlight that plant responses are species-specific and governed by interactive effects of temperature and $CO_2$ concentration. The significance of this article lies in its holistic perspective, which provides a complex framework for predicting plant adaptability under future climate scenarios by linking metabolism, phenology, and developmental responses. Understanding these mechanisms is crucial for protecting biodiversity, managing fisheries that rely on seagrass habitats, and predicting agricultural productivity. However, this study faces limitations as long-term distribution data is still relatively scarce for phenological records, and many mechanisms and pathways, especially molecular temperature sensors, have not been fully elucidated. Regional variability in precipitation and extreme events further complicates predictive accuracy. Future research should combine manipulative experiments—simulating simultaneous warming and $CO_2$ enrichment—with dynamic models that partition the relative influence of seasonal drivers. Advancements in genomic and phenomic tools will also be essential to unravel gene-environment interactions. By addressing these gaps, we can refine projections of vegetation dynamics and guide adaptive management strategies to mitigate the impacts of a changing climate.

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