The impact of climate change on plant physiology and adaptation mechanisms

[1] Daniela Bordea, [2] Maria Popescu

[1] Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Romania; [2] Equine Clinic, Faculty of Veterinary Medicine, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania. Corresponding author: D. Bordea, bordeadana@yahoo.com

Abstract. Climate change significantly affects plant physiology and necessitates various adaptation mechanisms. This essay explores how increased atmospheric CO_2 levels, temperature fluctuations, and altered precipitation patterns impact plant processes such as photosynthesis, respiration, and water use efficiency. Elevated CO_2 levels enhance photosynthesis, particularly in C3 plants, but benefits are moderated by nutrient availability. Temperature stress can disrupt metabolic functions, affecting plant growth and productivity, while changes in precipitation patterns influence water availability and plant health. Plants employ various adaptation strategies, including changes in stomatal conductance, synthesis of heat shock proteins, and metabolic adjustments, to cope with these stresses. The implications for biodiversity and agriculture are profound, with potential shifts in species distributions and the need for resilient crop varieties. Understanding these physiological responses and adaptations is critical for developing sustainable strategies to mitigate the effects of climate change on plant life.
Key Words: biodiversity, CO_2 fertilization, drought resistance, photosynthesis, sustainable agriculture.

Introduction. Climate change is perceived differently by different populations belonging to different cultures (Petrescu-Mag et al 2022a). The recent rapid climate changes are indisputable (Petrescu-Mag & Bănățean-Dunea 2022). Climate change poses one of the most significant challenges to ecosystems globally, affecting plant physiology and adaptation strategies (Oroian et al 2023). As the primary producers in most ecosystems, plants play a critical role in maintaining ecological balance and supporting life on Earth. This paper explores the physiological responses of plants to climate change, focusing on the impacts of increased atmospheric CO^2, temperature fluctuations, and altered precipitation patterns. It also examines the mechanisms of adaptation that plants employ to cope with these changes, offering insights into the future of plant biodiversity and agriculture.

Physiological Responses to Increased CO_2 Levels. One of the most direct effects of climate change is the rise in atmospheric carbon dioxide (CO_2) levels, which has implications for plant photosynthesis and growth (Fan et al 2020). CO_2 is a fundamental substrate for photosynthesis (Petrescu-Mag et al 2023a), and elevated levels can enhance photosynthetic rates - a phenomenon known as the CO_2 fertilization effect (Fan et al 2020). C3 plants (Figure 1), which use the Calvin cycle for carbon fixation, are particularly responsive to increased CO_2, showing enhanced growth and productivity under elevated CO_2 conditions (Lawson et al 2022). This response is partly due to reduced photorespiration, a process that normally consumes oxygen and releases CO_2, thus wasting energy (Raines et al 2022).

However, the benefits of increased CO_2 are not uniform across all plant species (Treves et al 2022). C4 plants, which utilize an additional CO_2 concentrating mechanism (Figure 1), show less pronounced responses to elevated CO_2 levels. Moreover, the positive effects of CO_2 fertilization can be limited by nutrient availability, particularly nitrogen and phosphorus, which are essential for protein synthesis and energy transfer in plants (Wang et al 2020a).

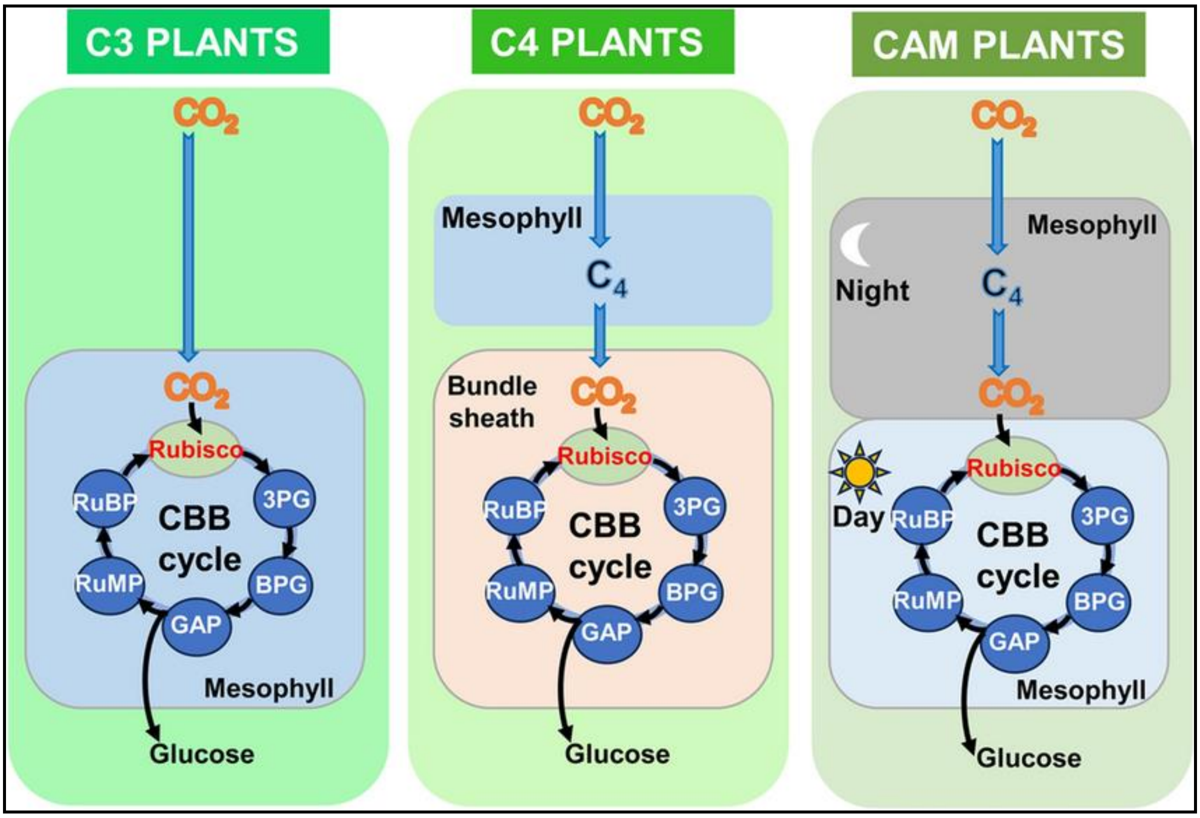

Figure 1. Schematic illustration of C3, C4, and the crassulacean acid metabolism (CAM) pathways of photosynthesis in plants (Stirbet et al 2024). C4, malate, a four-carbon compound that releases CO2 after decarboxylation; CBB cycle, Calvin-Benson-Bassham cycle of carbon assimilation; Rubisco, ribulose-1,5-bisphosphate carboxylase/oxygenase; 3PG, 3-phosphoglycerate; BPG, 1,3-bisphosphoglycerate; GAP, glyceraldehyde 3-phosphate; RuMP, ribulose 5-phosphate; RuBP, ribulose 1,5-bisphosphate. Source: Stirbet et al (2024), modified after https//ib.bioninja.com.au/higher-level/topic-8-metabolism-cell/untitled-2/c3-c4-and-cam-plants.html

Temperature Stress and Plant Metabolism. Rising global temperatures are another critical aspect of climate change, with profound effects on plant metabolism and growth (Zandalinas et al 2022). Temperature influences the rate of biochemical reactions within plants, including photosynthesis, respiration, and transpiration (Petrescu-Mag et al 2023b). Optimal temperatures vary among species, and deviations from these ranges can cause thermal stress, leading to reduced growth and reproductive success.

High temperatures can disrupt the stability of chloroplast membranes, impairing the function of photosystem II, a crucial component of the photosynthetic apparatus (Li et al 2021). This disruption can lead to a decrease in the efficiency of photosynthesis and an increase in photorespiration, thereby reducing overall plant productivity. Additionally, elevated temperatures can accelerate plant developmental processes (Jacott & Boden 2020), potentially shortening the growing season and affecting crop yields.

Changes in Precipitation Patterns. Climate change also affects precipitation patterns, leading to altered water availability, which is a critical factor in plant physiology (Wang et al 2020b). Increased frequency and intensity of droughts can lead to water stress, which affects stomatal conductance - the regulation of gas exchange in plants. Under water stress, plants typically close their stomata to reduce water loss through transpiration. However, this also limits CO_2 uptake, thereby reducing photosynthesis and growth.

Conversely, excessive rainfall can lead to waterlogged soils, causing hypoxic conditions that impair root function and nutrient uptake. Waterlogging can also lead to the production of ethylene (Pan et al 2021), a plant hormone that triggers responses such as leaf senescence and abscission, adversely affecting plant growth and survival.

Adaptation Mechanisms in Plants. Plants exhibit a range of physiological and morphological adaptations to cope with the stresses imposed by climate change. One key adaptation is the alteration of stomatal density and distribution (Liu et al 2021), which can optimize water use efficiency. For example, some plants may develop fewer stomata under water-limited conditions, reducing water loss while maintaining sufficient CO_2 uptake for photosynthesis (Hasanuzzaman et al 2023).

Similar to the case of animals (Petrescu-Mag et al 2007; Petrescu-Mag & Petrescu-Mag 2010), another adaptation of plants is the synthesis of heat shock proteins (HSPs), which help stabilize and refold denatured proteins under thermal stress (Bourgine & Guihur 2021). Plants can also accumulate compatible solutes, such as proline and glycine betaine (Ali et al 2020), which protect cellular structures and enzymes from damage caused by dehydration and high salinity.

In response to elevated CO_2, some plants may shift their photosynthetic pathways, such as adopting a more C4-like metabolism or enhancing the efficiency of the Calvin cycle (Burgess & Wang 2023). This metabolic flexibility allows them to better utilize available resources and maintain productivity under changing environmental conditions.

Implications for Biodiversity and Agriculture. The physiological responses and adaptation mechanisms of plants to climate change have significant implications for biodiversity and agriculture. Shifts in the distribution of plant species due to changing climate conditions can alter ecosystem composition and function (Oroian et al 2023). Species that are unable to adapt or migrate may face increased risks of extinction, leading to a loss of biodiversity (Oroian et al 2023).

In agriculture, the impact of climate change on crop physiology necessitates the development of resilient crop varieties (Petrescu-Mag et al 2022b). Breeding programs are increasingly focusing on traits such as drought tolerance, heat resistance, and efficient nutrient use to ensure food security in a changing climate. Biotechnology, including genetic engineering and CRISPR-Cas9, plays a vital role in accelerating the development of these traits (Bora & Papuc 2023; Petrescu-Mag & Burny 2023).

Conclusions. Climate change poses multifaceted challenges to plant physiology and survival, influencing processes such as photosynthesis, respiration, and water use. Plants exhibit a range of adaptation mechanisms to cope with these stresses, from morphological changes to biochemical responses. Understanding these physiological responses and adaptations is crucial for predicting the future of plant biodiversity and developing strategies to sustain agriculture in a warming world. As research continues, it is essential to integrate knowledge from plant physiology, ecology, and genetics to address the complex impacts of climate change on plant life.

Conflict of Interest. The authors declare that there is no conflict of interest.

References

Ali S., Abbas Z., Seleiman M. F., Rizwan M., YavaŞ İ., Alhammad B. A., Shami A., Hasanuzzaman M., Kalderis D., 2020 Glycine betaine accumulation, significance and interests for heavy metal tolerance in plants. Plants 9(7):896.

Bora F. D., Papuc T., 2023 The role of CRISPR-Cas9 in advancing plant biotechnology. AAB Bioflux 15(2):131-134.

Bourgine B., Guihur A., 2021 Heat shock signaling in land plants: from plasma membrane sensing to the transcription of small heat shock proteins. Frontiers in Plant Science 12:710801.

Burgess A. J., Wang P., 2023 Not all Calvin's are equal: Differential control of the Calvin cycle in C3 versus C4 plants. Plant Physiology 191(2):817-819.

Fan X., Cao X., Zhou H., Hao L., Dong W., He C., Xu M., Wu H., Wang L., Chang Z., Zheng Y., 2020 Carbon dioxide fertilization effect on plant growth under soil water stress associates with changes in stomatal traits, leaf photosynthesis, and foliar nitrogen of bell pepper (*Capsicum annuum* L.). Environmental and Experimental Botany 179:104203.

Hasanuzzaman M., Zhou M., Shabala S., 2023 How does stomatal density and residual transpiration contribute to osmotic stress tolerance? Plants 12(3):494.

Jacott C. N., Boden S. A., 2020 Feeling the heat: developmental and molecular responses of wheat and barley to high ambient temperatures. Journal of Experimental Botany 71(19):5740-5751.

Lawson T., Emmerson R., Battle M., Pullin J., Wall S., Hofmann T. A., 2022 Carbon fixation. In: Photosynthesis in action. Academic Press, pp. 31-58.

Li D., Wang M., Zhang T., Chen X., Li C., Liu Y., Brestic M., Chen T. H. H., Yang X., 2021 Glycinebetaine mitigated the photoinhibition of photosystem II at high temperature in transgenic tomato plants. Photosynthesis Research 147:301-315.

Liu C., Li Y., Xu L., Li M., Wang J., Yan P., He N., 2021 Stomatal arrangement pattern: a new direction to explore plant adaptation and evolution. Frontiers in Plant Science 12:655255.

Oroian F. C., Kovacs E., Bora F. D., Popescu M., 2023 Adapting agricultural crops to new regional climates post-climate change. AAB Bioflux 15(2):115-121.

Pan J., Sharif R., Xu X., Chen X., 2021 Mechanisms of waterlogging tolerance in plants: Research progress and prospects. Frontiers in Plant Science 11:627331.

Petrescu-Mag I. V., Bănățean-Dunea I., 2022 Measurements of the diameter of the fig stem (*Ficus carica*) in Romania for six years show the transition from a small shrub to a tree-like plant. Research Journal of Agricultural Science 54(2):131-135.

Petrescu-Mag I. V., Botha M., Petrescu-Mag R. M., 2007 Heat shock proteins in fish – a review. ELBA Bioflux Pilot (a):1-10.

Petrescu-Mag I. V., Burny P., 2023 A review of wheat cultivation and its cultural significance. AAB Bioflux 15(1):25-36.

Petrescu-Mag I. V., Oroian F. C., Burduhos P., Kovacs E., 2023a Climate, carbon, solutions and perspectives. AAB Bioflux 15(2):73-82.

Petrescu-Mag I. V., Petrescu-Mag R. M., 2010 Heavy metal and thermal stress in fishes: The implications of HSP in adapting and acclimation to different environments. Metalurgia International 15(10):107-117.

Petrescu-Mag I. V., Popescu M., Gavriloaie C., 2023b Photosynthetic plants that thrive without humus-rich soil. AAB Bioflux 15(2):122-126.

Petrescu-Mag R. M., Burny P., Bănățean-Dunea I., Petrescu D. C., 2022a How climate change science is reflected in people's minds. A cross-country study on people's perceptions of climate change. International Journal of Environmental Research and Public Health 19(7):4280.

Petrescu-Mag R. M., Petrescu D. C., Muntean O. L., Petrescu-Mag I. V., Radu Tenter A., Azadi H., 2022b The nexus of traditional knowledge and climate change adaptation: Romanian farmers' behavior towards landraces. Local Environment 27(2):229-250.

Raines C. A., Cavanagh A. P., Simkin A. J., 2022 Improving carbon fixation. In: Photosynthesis in action. Academic Press, pp. 175-192.

Stirbet A., Guo Y., Lazár D., Govindjee G., 2024 From leaf to multiscale models of photosynthesis: Applications and challenges for crop improvement. Photosynthesis Research 161(1-2):21-49.

Treves H., Küken A., Arrivault S., Ishihara H., Hoppe I., Erban A., Höhne M., Moraes T. A., Kopka J., Szymanski J., Nikoloski Z., Stitt M., 2022 Carbon flux through photosynthesis and central carbon metabolism show distinct patterns between algae, C3 and C4 plants. Nature Plants 8(1):78-91.

Wang F., Gao J., Yong J. W., Wang Q., Ma J., He X., 2020a Higher atmospheric CO_2 levels favor C3 plants over C4 plants in utilizing ammonium as a nitrogen source. Frontiers in Plant Science 11:537443.

Wang P., Huang K., Hu S., 2020b Distinct fine-root responses to precipitation changes in herbaceous and woody plants: a meta-analysis. New Phytologist 225(4):1491-1499.
Zandalinas S. I., Balfagón D., Gómez-Cadenas A., Mittler R., 2022 Plant responses to climate change: metabolic changes under combined abiotic stresses. Journal of Experimental Botany 73(11):3339-3354.
*** https//ib.bioninja.com.au/higher-level/topic-8-metabolism-cell/untitled-2/c3-c4-and-cam-plants.html

Received: 12 October 2023. Accepted: 28 November 2023. Published online: 28 December 2023.
Authors:
Daniela Bordea, Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Mănăștur Street, 400372 Cluj-Napoca, Romania, e-mail: bordeadana@yahoo.com
Maria Popescu, Equine Clinic, Faculty of Veterinary Medicine, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Mănăștur Street, 400372 Cluj-Napoca, Romania, e-mail: maria.popescu@usamvcluj.ro

How to cite this article:
Bordea D., Popescu M., 2023 The impact of climate change on plant physiology and adaptation mechanisms. AAB Bioflux 15(2):135-139.