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Crop production in a changing climate: Impacts and adaptive strategies

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Abstract
Climate change significantly impacts crop production through rising temperatures, unpredictable precipitation, and increased greenhouse gas concentrations. These changes threaten global food security by affecting plant growth, yield, and nutritional quality. Elevated CO_2 levels may enhance photosynthesis in C3 plants but can also alter crop physiology, nutrient composition, and water-use efficiency. Additionally, climate change intensifies biotic stresses such as pests and diseases. Adaptation strategies, including stress-tolerant crop varieties, precision farming, improved irrigation, and genomic advancements like CRISPR, are crucial to ensuring agricultural sustainability. By integrating innovative technologies and sustainable practices, crop resilience can be enhanced, securing food production in the face of environmental challenges.

Keywords: Climate change, crop productivity, CO_2 elevation, drought stress, plant physiology, genetic engineering, sustainable agriculture

Introduction
Climate change refers to long-term shifts in weather patterns, influenced by both natural phenomena and human activities. While climate changes due to factors like volcanic activity and earth's orbit have occurred throughout history, human actions, especially fossil fuel combustion and land-use changes have significantly increased greenhouse gases like carbon dioxide (CO_2), methane and nitrous oxide since the Industrial Revolution. This has led to global warming and made climate change a major environmental concern with far-reaching impacts on agriculture (UNFCCC, 2006) [33].

Agriculture is highly vulnerable to climate change, with crop productivity affected by temperature increases, water scarcity and changes in CO_2 levels. Over the last century, global surface temperatures have risen by 0.85 °C and further warming is expected which threatens crop yields. As CO_2 concentrations rise from 280 µmol−1 to 400 µmol−1 with projections to reach 800 µmol−1 by the end of the century, extreme conditions like heat, drought and salinity intensify stresses on crops. Drought is expected to limit productivity in half of the world's arable land in the next 50 years and rising competition for water will worsen the issue (Sinclair *et al.*, 2010) [28]. Temperature changes are also projected to shorten growing seasons and reduce grain yields, while elevated CO_2 could lower protein and micronutrient concentrations in grains (Ziska *et al.*, 2004) [35]. While higher CO_2 concentrations could potentially boost crop yields in some areas, optimal conditions such as nutrient levels, soil moisture and water availability are crucial for this benefit to materialize. Additionally, farming practices and technology play a role in determining the overall impact of climate change on agricultural production (Hatfield *et al.*, 2011) [18].

Biotic factors like pests and diseases are also affected by climate change, with warmer temperatures leading to more severe infestations (Coakley *et al.*, 1999) [11]. These combined stresses may lead to reduced productivity, higher food prices and greater food insecurity, especially in developing regions.

To ensure food security, climate-smart crop cultivars and adaptation strategies, such as drought-resistant crops, are essential. As the global population grows, innovative approaches, including genetic engineering are necessary to create crops resilient to changing climates, ensuring food security amid global warming.

Physiological Response of plants to climate change

Plants are categorized into C3, C4 and CAM types based on their photosynthetic pathways. Each of them responds differently to atmospheric CO_2 levels. C3 plants (e.g., wheat, rice) experience higher photorespiration rates, whereas C4 plants (e.g., maize, sugarcane) are less affected, making them more efficient in high CO_2 conditions (Fantahun, 2013) [16]. Elevated CO_2 enhances photosynthesis and growth, especially in C3 plants, but its benefits can be offset by climate change factors like increased temperature and altered precipitation (Easterling *et al*., 2007) [15]. C3 plants benefit more from elevated CO_2 at moderate temperatures, while C4 plants show consistent growth improvements. Studies show that elevated CO_2 can increase biomass in both C3 and C4 plants, with C3 species showing greater tiller formation and C4 species expanding leaf area. Additionally, elevated CO_2 improves drought resistance and heat tolerance in plants, although nutrient deficiencies may arise (Niinemets, 2010) [26]. Climate change poses significant risks, specially for tropical regions, potentially reducing crop yields (Tubiello & Fischer, 2007) [30].

Elevated CO_2 levels lead to various physiological changes in plants, including increased mesophyll cell production, chloroplasts, longer stems and enhanced root growth, resulting in better root-to-shoot ratios and altered branching patterns. Crop productivity tends to increase within a local temperature range of 1-3 °C, but decreases beyond this range due to factors like reduced vernalization, shorter phenological phases, decreased photosynthesis and increased transpiration (IPCC, 2023). Some annual C3 crops, such as soybean, peanut and rice, experience accelerated growth, earlier flowering and higher grain yields under elevated CO_2 (Uprety *et al*., 2010) [31]. However, C4 crops like maize show yield reductions due to shortened growing periods and some winter wheat cultivars also face yield declines (Alexandrov & Hoogenboom, 2000) [1]. Conversely, cotton exposed to elevated CO_2 levels showed significant yield and biomass increases (Easterling *et al*., 2007) [15]. Responses vary depending on water, environmental variability significantly impacts plant adaptation, with climate extremes affecting physiological processes. Elevated temperatures above 35 °C hinder plant growth and photosynthesis, while drought stress limits turgor pressure and impairs cell development, reducing photosynthesis efficiency. Increased CO_2 levels can affect respiration, particularly at higher temperatures, disturbing morphological traits (Atkin *et al*., 2005) [4]. The enzyme Rubisco, crucial for CO_2 fixation, becomes less efficient at higher temperatures due to deactivation by Rubisco activase. Additionally, rising temperatures and stress increase reactive oxygen species (ROS), which are regulated by antioxidant mechanisms but can cause damage under stress.

Photosynthesis and Plant Respiration Response of plants to climate change

Temperature and CO_2 levels significantly affect plant respiration and photosynthesis. Respiration is driven by carbohydrate status and adenylate supply, with mitochondrial respiration being crucial for plant growth and survival (Atkin *et al*., 2005) [4]. Elevated CO_2 can increase respiration temporarily in parts of plants, but long-term exposure may reduce whole-plant respiration. Temperature also influences respiration, with plants in cold climates, such as the Arctic, experiencing more significant effects than those in tropical regions (Atkin & Tjoelker, 2003) [5]. Photosynthesis in C3 plants is influenced by both CO_2 and temperature, as Rubisco's affinity for CO_2 increases with higher CO_2 levels improving photosynthesis. Water availability is crucial for photosynthesis as stomatal closure reduces both water loss and CO_2 intake (Kirschbaum, 2014) [21]. Experiments show that C3 photosynthesis increases by 25-75% with doubled CO_2, while C4 plants show smaller responses (Asseng *et al*., 2015) [3]. FACE experiments also support sustained growth increases in elevated CO_2 conditions (Tkemaladze*et al*., 2016, Kurepin *et al*., 2017) [29, 22].

Plant Hormone Response of plants to climate change

Phytohormones, such as abscisic acid (ABA), salicylic acid (SA) and ethylene, play essential roles in plant responses to abiotic stresses. ABA is crucial for regulating drought stress, seed dormancy and stomatal control by interacting with other hormones through signaling cascades like PYR/PYL/RCAR-PP2C-SnRK2. Under drought conditions, ABA concentration increases, leading to stomatal closure and reduced transpiration to conserve water (Arnao *et al*., 2017) [2]. SA regulates various physiological processes, including cell cycle regulation, fruit productivity, temperature resistance and senescence, by modulating stress-responsive genes (Malamy *et al*., 1990) [25]. Ethylene, a gaseous hormone, helps coordinate seed germination, ripening and senescence under abiotic stresses like salinity, drought and high temperature (Wang *et al*., 2018) [34]. Ethylene response factors (ERFs), activated by stress are transcription factors involved in regulating plant responses to environmental changes. These hormones together enable plants to adapt and survive in variable climates.

Crop Adaptation to Climate change Stresses

Climate change, driven by rising global temperatures, is severely affecting agricultural productivity, specially through drought, heat and cold stress. These environmental stresses disrupt plant growth and yield, impacting key crops like wheat, rice and maize. Wheat, a major staple crop, faces reduced productivity under warmer conditions, with predictions of up to a 6% yield decrease due to temperature rises. Adaptation to climate change in agriculture is crucial to minimize these impacts. It involves modifying crops and farming practices to increase resilience, such as developing stress-tolerant crops and adjusting agricultural systems to manage new climate extremes. Adaptation strategies include improving water management, altering crop schedules and adopting new technologies. Both anticipatory and reactive measures are necessary, including diversification of crops and community-based disaster risk reduction. Effective climate change adaptation in agriculture is vital for food security and reducing vulnerability to climate-related challenges. The adaptation of crops to climate change involves leveraging emerging technologies, scientific expertise and resources. Historically, farmers have adjusted crop varieties and practices in response to environmental changes but the accelerated pace of climate change poses unprecedented challenges. As global temperatures rise, extreme weather events like drought, intense precipitation and elevated temperatures will impact crop yields and quality, making food security increasingly difficult (Hatfield *et al*., 2011) [18]. Understanding how plants physiologically respond to these changes is crucial for predicting species distributions and developing effective conservation strategies.

Plants, being sessile organisms, cannot escape stress factors like animals can. This has driven them to develop unique molecular mechanisms to cope with abiotic stress, such as drought and heat. These mechanisms include the activation of signaling pathways, altered gene expression, accumulation of compatible solutes, synthesis of stress proteins and enhanced antioxidative metabolism. Other strategies include ion homeostasis, facilitated membrane transport and hormonal adjustments, which allow plants to better tolerate adverse conditions (Madhava *et al*., 2006) [24].

Approaches to Combat Climate Changes

Cultural Methodologies

Farmers are increasingly adopting various strategies to help plants adapt to climatic variations. These strategies include modifying abiotic factors such as planting and harvesting times, selecting crops with shorter life cycles, rotating crops and adjusting irrigation methods. Such practices help crops become more resilient under stressful climate conditions and are particularly valuable for enhancing crop adaptability (Duku *et al*., 2018) [14]. Key methods include changing sowing dates, using drought-resistant cultivars and introducing new crops, which mitigate risks associated with climate variability and ensure food security. Furthermore, crop management techniques such as optimizing sowing time, planting density and irrigation practices are essential for improving crop growth under diverse environmental stresses. Fertilizers also play a significant role in helping crops cope with global warming by providing essential nutrients and boosting plant energy. They contribute to soil fertility, enhancing productivity and supporting agricultural sustainability. Overall, these cultural methodologies are crucial for improving plant adaptability and safeguarding food security amid changing climate conditions, underlining the undeniable importance of fertilizers in modern agriculture (Henderson, 2018) [19].

Develop New Crops

The development of new crops and the integration of beneficial traits into existing crops are crucial for addressing climate change challenges in agriculture. Domestication of crops such as maize, wheat and rice began thousands of years ago, with recent efforts focusing on crossing wild perennial relatives with domesticated crops to enhance resilience. This long-term solution is complemented by a growing interest in bioenergy crops like switchgrass and Miscanthus (Bransby *et al*., 2010) [7]. Breeding new crops and improving germplasm collections for traits like drought, heat and waterlogging tolerance are key to achieving higher yields under climate stress. Germplasm banks and modern biotechnology methods are being used to screen for adaptive traits, allowing faster identification of stress-resistant genes (CSSA, 2011) [12]. Additionally, specific germplasm with tolerance to pathogens, insects and nematodes is being identified, as climate change may alter pest-crop interactions (Gregory *et al*., 2009) [17]. New cropping systems are also being developed, focusing on site-specific management practices tailored to regional vulnerabilities. Crop models are increasingly used to guide decision-making, allowing farmers to optimize genetics, crop management and environmental conditions. These strategies collectively aim to ensure sustainable crop production in the face of climate change.

Use of Remote Sensing and Precision Farming Technologies

Remote sensing using both satellite and on-the-go field scanners can reduce the resources needed to measure crop characteristics like cover, leaf greenness, growth rate and biomass across a broad range of cropping systems and environments. This information then allows researchers to assess the effectiveness of modifications in cropping systems and can help producers make precision agriculture production decisions at the field scale. These tools will be of great use in understanding the effects of a changing environment at the field scale and the appropriate agronomic methods needed to respond to such changes.

Monitoring Crop Condition

Short- and long-term monitoring of factors such as pathogens, changes in field conditions, crop productivity and weather patterns is essential for building an information base on which future decisions and innovations can draw from. Remote sensing of crop, weather and pest conditions, for example, can be used by farmers for adaptive management or by governments as an early warning signal for climate-based food security crises.

Optimization of Water-Use Efficiency With climate change, water supplies are expected to become threatened in certain regions of the world, but water management strategies, such as drip irrigation, can conserve water and protect vulnerable crops from water shortages.

Optimizing Land Use

Intensifying yields sustainably on existing arable land uses land more efficiently and avoids bringing new land into production. Higher yields have also been shown to reduce greenhouse gas emissions, thus helping minimize agriculture's contribution to climate change (Burney *et al*., 2010) [8].

Conventional Breeding Techniques

Plant breeding plays a crucial role in developing crops that can withstand various environmental stresses, thus ensuring food security under changing climatic conditions. Through breeding, stress-resistant cultivars can be created, helping plants survive harsh weather variations and escape different stressors during critical stages of growth (Blum *et al*., 2018) [6]. Genetic divergence analysis is a key tool in this process, as it assesses polymorphism, inbreeding, assortment and recombination to achieve plant perfection. This method helps in the development of new cultivars by evaluating genetic distances and similarities, aiding the creation of varieties that are more resilient to stress. Landraces, particularly those stored in gene banks, are valuable genetic resources for breeding stress-resistant crops, as they exhibit a broader genetic variance and adaptability to diverse environmental stresses. For example, wheat landraces are a key source of genetic variation that can be utilized for stress resistance (Lopes *et al*., 2015) [23]. Molecular and integrated plant breeding approaches, such as marker-assisted selection (MAS) and genome-wide association studies (GWAS), are essential tools in developing cultivars with enhanced biotic and abiotic stress tolerance. These genomic techniques enable breeders to select traits more efficiently and accelerate the development of crops capable of thriving under environmental stresses.

Advance Genetics and Genomics Strategies

Omics-led breeding and Marker-Assisted Selection (MAS) have significantly advanced crop improvement, focusing on enhancing traits like stress tolerance and yield. These methods utilize genomics, transcriptomics, and phenomics to identify key traits with molecular markers such as SNPs and QTL mapping aiding the development of stress-resistant crops. QTL mapping has been instrumental in identifying drought resistance genes in wheat and maize while Genome-Wide Association Studies (GWAS) have uncovered SNPs linked to stress tolerance in crops like rice and sorghum (Verslues *et al*., 2013; Qin *et al*., 2016) [32, 27]. These tools, combined with high-throughput sequencing enable the rapid selection of elite germplasm suited for climate-smart agriculture (Chopra *et al*., 2017) [11].

Genomic selection (GS), particularly in crops like wheat and maize, leverages high-density markers and phenotypic data to accelerate breeding progress. GS focuses on improving polygenic traits and adaptability to environmental stress, using models like G × E and Bayesian-based models for accurate trait prediction (Cuevas *et al*., 2017) [13]. Wheat, a leader in GS research, has benefited from markers such as SNPs and DArT, enhancing resilience to heat and drought stress.

Genetic engineering (GE) and genome editing (GE) tools like CRISPR/Cas9 have further revolutionized crop breeding. Transgenic plants modified with transcription factors (TFs), such as DREB and MYB families, have shown improved resistance to stresses like drought and salinity (Zhu *et al*., 2016) [36]. CRISPR/Cas9, in particular, offers precise genome manipulation to enhance stress tolerance and yield. By targeting genes linked to abiotic stresses, such as TaERF3 and TaDREB2 in wheat, or modifying traits like seed size in rice and Brassica napus, CRISPR has demonstrated its potential for improving crop resilience (Klap *et al*., 2017) [9]. Integration of genomics technologies, genomic selection, GE, and CRISPR/Cas9 is crucial for developing crops that can thrive under changing environmental conditions, ensuring enhanced productivity and resilience in agriculture.

Conclusion

Industrialization, population growth and urbanization have led to increased greenhouse gas (GHG) emissions and a higher demand for natural resources both renewable and non-renewable. These changes result in climate disruptions that impact agriculture, specially through abiotic stresses such as temperature fluctuations, drought and unpredictable rainfall. These environmental changes negatively affect crop growth and yield, making it imperative to optimize plant responses to climate variability. One major challenge is addressing the molecular and physiological bottlenecks in plants that hinder their adaptation to abiotic stresses.

To mitigate these challenges the adoption of sustainable practices and technologies is essential. Efforts must focus on reducing emissions and protecting natural resources for future generations. Climate change adaptation strategies require technology, suitable policies and guidelines that are socially acceptable and environmentally sustainable. Ongoing awareness about climate change and its impacts is crucial for fostering community participation in adaptation processes.

To combat the adverse effects of climate change on agriculture, research must focus on improving crop resistance to both abiotic and biotic stresses. Approaches such as genome-wide association studies (GWAS), genomic selection (GS) and CRISPR/Cas9-mediated genome editing are key tools for developing climate-resilient crops. Breeding methods along with novel cultural practices and cropping schemes, will be necessary to ensure that plants can thrive under extreme conditions like drought and heat. Additionally, eco-friendly genetic engineering strategies will play a vital role in creating crops that can withstand future climate challenges, ensuring food security in the face of environmental uncertainties. In conclusion, climate change demands adaptive strategies for crop survival and agricultural productivity. Industrialization, population growth and urbanization exacerbate the challenges by increasing greenhouse gas emissions and resource demand. To address these issues, it is crucial to reduce emissions and manage natural resources sustainably. Adaptation strategies should be technologically driven, socially acceptable and environmentally sustainable. Public awareness and community involvement in climate change adaptation are essential. Additionally, ongoing research on plant species responses to climate variability will help identify those most vulnerable and guide conservation efforts to protect biodiversity and ecosystem.

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