

The effects of climate change on the yield gap of crops

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Abstract

The amount and quality of agricultural yield can vary significantly due to the considerable impact of management practices and environmental factors on production. Climate change results in alterations to weather patterns and resources, which interrupts the growth and development cycle of plants and greatly impacts the widening of the yield gap. Some of the impacts of climate change include reduced rainfall distribution and duration, rising temperatures, diminished soil ventilation capacity, heightened risk of droughts and floods, increased abiotic stresses, and alterations in the behavior and characteristics of pathogens and pests. Conversely, the rise in both the frequency and severity of extreme weather events, like tornadoes and hurricanes, is another consequence of climate change affecting agricultural ecosystems, resulting in a widening yield gap. Given the ongoing climate changes and the arid and semi-arid regions of Iran, it is essential to adapt different plant characteristics and implement management strategies to address the stresses brought on by climate change, such as drought, heat, and shifts in precipitation patterns. This is crucial for narrowing the yield gap of crop plants in the years ahead.

Key words: Agricultural ecosystem, precipitation, temperature, stress, yield gap

Introduction

Among the most important environmental challenges that have attracted the attention of many scientific and political circles of the world in the last two decades is Climate Change. Climate changes are long-term changes in weather conditions and indicators (temperature, precipitation, wind, relative humidity, evaporation and transpiration, etc.). Climate change factors may be natural anomalies or human activities (Figure 1) (Malhi *et al.*, 2021; Aryal *et al.*, 2020; Skendžić *et al.*, 2022; Arora *et al.*, 2019).

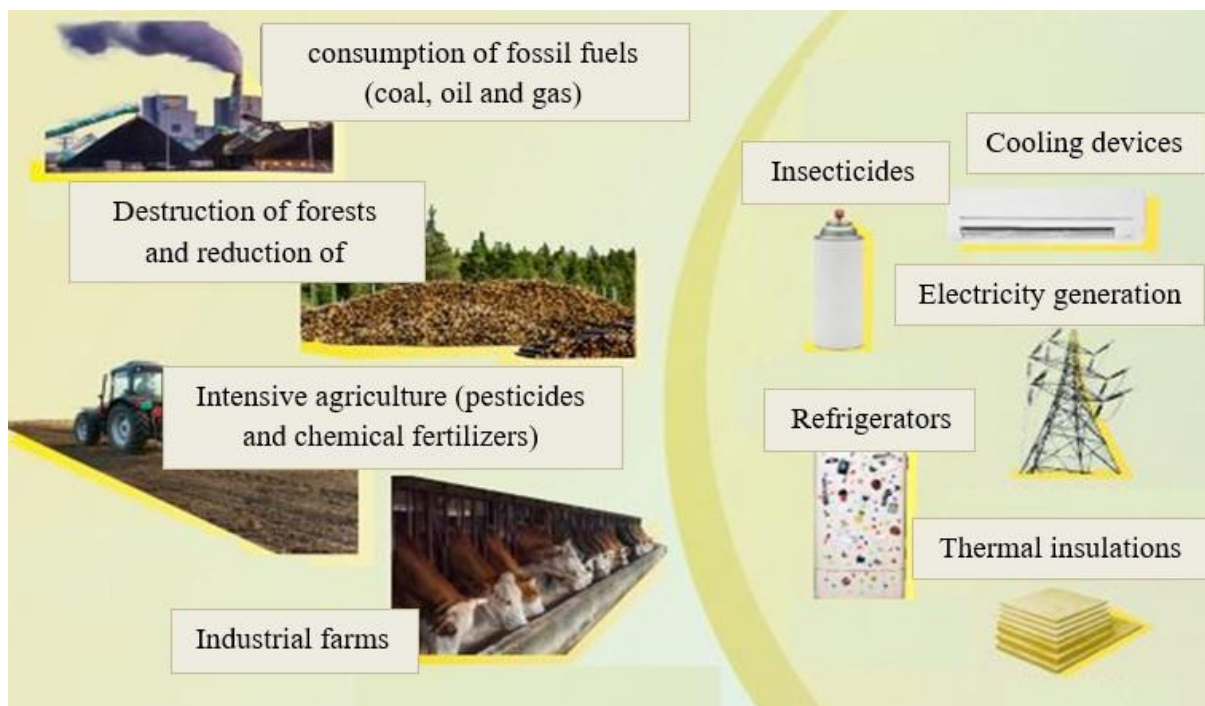


Figure 1. Schematic of the most important human activities effective in increasing climate change

One of the most basic climate indicators that have changed drastically in the last 100 years is the increase in the earth's temperature. A large part of the natural warming of the air is due to human activities, including the emission of greenhouse gases (methane, water vapor, carbon dioxide, chlorofluorocarbons, hydrofluorocarbons, and dinitrogen monoxide), some greenhouse gases respond to temperature changes and change, water vapor is one of It is these gases that show feedback to the temperature. On the other hand, some gases do not respond chemically or physically to temperature changes and remain in the atmosphere almost permanently with their long-term durability. These types of gases are called climate-imposing gases that cause radiative forcing. The contribution of carbon dioxide to the occurrence of such a phenomenon is greater than other greenhouse gases, so it has the greatest effect on increasing the temperature of the earth's surface (Lobell *et al.*, 2015; Kumar *et al.*, 2018).

As per climate change models, the average global temperature is projected to rise by 4 to 6 degrees Celsius by the year 2100 (Figure 2). Moreover, current climate change models indicate that these changes will be more pronounced in arid and semi-arid regions (Chakraborty & Veerasha, 2024; Chauhan *et al.*, 2014; Alkolibi, 2002; Schauburger *et al.*, 2017). Analyzing climate change models indicates that in middle latitudes, temperatures will increase and precipitation patterns will change. Higher latitudes and tropical regions are expected to benefit from these changes. However, plain areas in central North and South America, southern Europe, southern Australia, and semi-arid and sub-tropical parts of Asia will experience the most severe conditions. Conversely, Northern Europe, Canada, Russia, Northeast and Southeast Asia, temperate regions of America, and cold mountainous regions will become warmer (Chakraborty & Veerasha, 2024; Saadi *et al.* 2015).

Changes in precipitation patterns, like temperature, are among the most noticeable effects of climate change worldwide. However, the extent of these changes varies across different geographical areas. For instance, predicted changes in rainfall are largely negative in many parts of the Americas and Asia, as well as in portions of Canada and Australia. On the other hand, most areas of Europe are expected to experience positive changes, characterized by an increase in annual rainfall. Overall, estimates from forecasting models suggest that dry and semi-arid regions of the world will become even drier (Huang *et al.*, 2016; Singh *et al.*, 2021)

It is projected that by the end of the 21st century, soil moisture depletion and the frequency of short-term droughts will double, while long-term droughts will triple, particularly in regions with lower precipitation (Singh *et al.*, 2021).

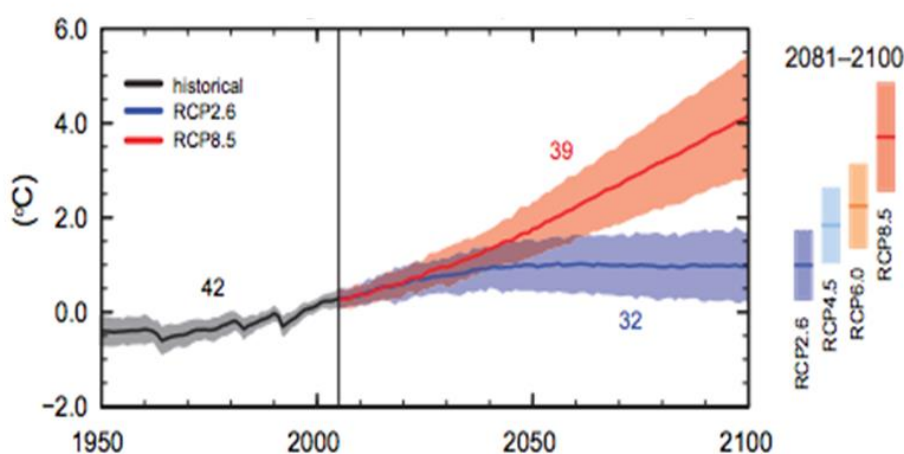


Figure 2. Future global warming prediction model under different scenarios

The consequences of climate change, particularly global warming, include drought, sea level rise, violent storms, weather disasters, reduced freshwater resources, warming air, forest fires, and desertification. One of the notable impacts of climate change is its effect on the agricultural sector. The agricultural sector is particularly vulnerable to the risks of climate change and global warming due to its heavy reliance on weather patterns and indicators (Chauhan *et al.*, 2014; Alkolibi, 2002; Schaubberger *et al.*, 2017).

The anticipated climate changes, particularly in temperature and rainfall, will alter the spread and distribution of agriculture in different regions. Conversely, regions with dry and semi-arid climates, such as Iran, are frequently plagued by droughts, leading to a 50 to 80% reduction in crop yields. It is anticipated that these changes will lead to a decline in food production potential, especially after 2050. According to the predictions of the Peterson Institute in the field of agricultural economics, the production of agricultural products in developing countries will decrease by 15-25% by 2050. As the population increases, the demand for food is expected to double in the coming years, while the impacts of global warming and water scarcity will further diminish production in most regions. This highlights the need to focus on addressing constraints on agricultural production and knowing the factors influencing the yield gap (Rayees *et al.*, 2013; Ostberg *et al.*, 2018; Johkan *et al.*, 2011; Janni *et al.*, 2024). The various aspects of climate change, including increasing carbon dioxide levels, rising temperatures, alterations in precipitation quantity and distribution, and changes in evaporation and transpiration patterns, can have diverse impacts on plant productivity. When these effects are combined, they can either increase or decrease production. Ultimately, the overall impact of climate change on agricultural productivity depends on the interactions between these different elements. In an agricultural ecosystem, all its components (such as soil, plants, microorganisms, humans, and insects) are interconnected and function as a unified whole. It is essential to consider these components collectively rather than separately. Climate change affects all aspects of agricultural ecosystems, and as a result, these changes can lead to both quantitative and qualitative changes in productivity (Johkan *et al.*, 2011; Raza *et al.*, 2019).

In a specific region, the yield gap is the difference between the yield potential and the actual yield obtained in the fields of farmers in that region. Various research on the effects of climate change on the yield gap of plants shows that changes in climate indicators, especially temperature, precipitation and carbon dioxide, have a significant role in increasing and decreasing the yield gap (Wakatsuki *et al.*, 2023). Global warming directly affects the rate of respiration photosynthesis and other biochemical mechanisms of plants. Absorption of

minerals, nutrients, and water, plant gas exchange, absorption of solar energy to produce carbohydrates during the photosynthesis cycle, as well as the metabolism of carbohydrates in respiration, are highly dependent on the level of carbon dioxide (CO₂), atmosphere, and ambient temperature. Soil biological processes such as decomposition, mineralization, and stabilization, and soil abiotic processes such as solute transport, aeration, ion exchange, etc. in soil are affected by climate change, which can affect all components of plant yield (potential, gap, and real yield) directly and indirectly (Sembiring *et al.*, 2019; Wakatsuki *et al.*, 2023). As the soil temperature rises, the rate of decomposition of organic matter increases, and the absorption of nutrients by the plant changes. Even if plants have mechanisms to tolerate adverse conditions (biotic and abiotic stresses), the physiological response of the plant to climate change depends on the limiting factors in the Vegetative places. For example, an increase in temperature causes reduced air vapor pressure and, as a result, an increase in transpiration, especially in dry areas (Figure 3) (Wakatsuki *et al.*, 2023).

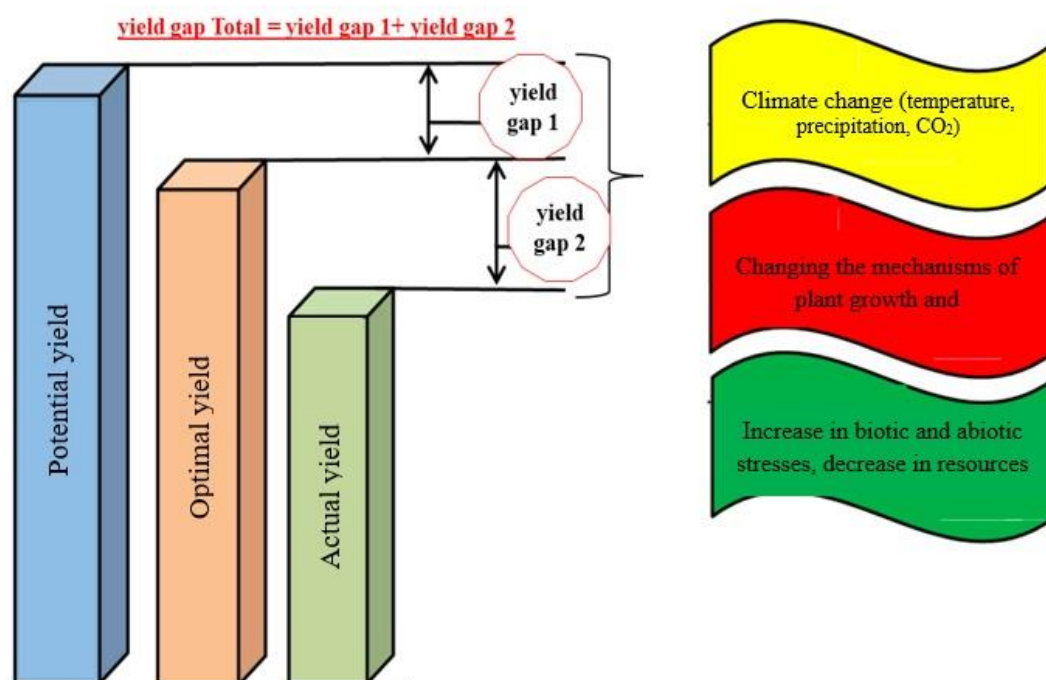


Figure 3. Schematic of understanding the yield gap compared to actual and potential yield and the most important effects of climate change in increasing yield gap

Given the impacts of climate change on climatic indicators, especially temperature, precipitation, and carbon dioxide, these changes play a significant role in increasing non-biological stresses and the growth cycle of biological stresses in agricultural ecosystems. This study aims to review the effects of climate change on the performance of crops.

Increasing carbon dioxide concentration and yield gap

Although CO₂ only makes up a very small percentage (0.03) of the atmosphere, it is a crucial component for the photosynthesis of plants. Without it, plants and living organisms cannot survive. The concentration of CO₂ has risen from about 270 mg/liter before the Industrial Revolution to about 410 mg/liter in 2023. Predictions suggest that its concentration will increase by 1.8 mg/liter every year, so that by 2050 the CO₂ concentration will be around 550 mg/liter, and by the end of this century, it could reach 800 mg/liter. CO₂ emissions will greatly depend on future actions (Allen *et al.*, 2024; Emmert *et al.*, 2012).

The rise in atmospheric CO₂ concentration has sparked numerous hypotheses and experiments regarding its potential effects on the growth and performance of plant vacuoles. It has been reported that three-carbon plants may experience a growth increase of 33-40%, while four-carbon plants may see a growth increase of 10-15% as a result of atmospheric CO₂ enrichment. CO₂ primarily affects plant processes through its direct impact on photosynthesis, stomatal performance, and efficiency. Increasing CO₂ levels have been found to reduce stomatal conductance and transpiration, enhance water use efficiency, intensify photosynthesis, and improve light use efficiency. These effects could significantly impact agricultural production systems and crop yields. Most studies have demonstrated that agricultural plants generally respond positively to increasing CO₂ levels (Allen *et al.*, 2024; Woodward, 2002; Ainsworth *et al.*, 2020).

The impact of increasing CO₂ concentration on plant production and productivity depends on other limiting factors such as water and nutrient availability, as well as the plant's photosynthetic capacity. In high CO₂ concentrations, the increase in photosynthesis intensity leads to enhanced plant growth and yield, but this is often restricted in soils lacking essential nutrients. Climate change-induced droughts are a major factor in reducing water and soil resources in agricultural ecosystems. Overall, the lack of essential nutrients limits the plants' capacity to utilize available carbon, indicating that short-term climate changes can reduce plant performance. Nevertheless, considering the long-term photosynthetic capacity and resource limitations, plant performance improves. Additionally, increased carbon dioxide boosts the host plant's metabolic rate, which is a key factor determining the increased activity of plant

pathogens (biological stresses) (Wang et al., 2012; Ainsworth *et al.*, 2020; Walsh *et al.*, 2024; Amthor, 2001; McDowell et al., 2022). As mentioned, an increase in carbon dioxide enhances the process of photosynthesis but reduces the transfer rate of metabolites and photosynthetic materials, which can also play an important role in increasing the yield gap (Singh *et al.*, 2023).

One important factor affecting plant health is the behavior of pathogens in the environment (Mootab *et al.*, 2023). Climate change, particularly the rise in carbon dioxide levels, has an impact on pathogens, plants, and their carriers. Changes in precipitation patterns, rising temperatures, and increased carbon dioxide directly influence the dynamics and outbreaks of plant diseases. Additionally, factors such as altered crops and shifts in the distribution and activity of carriers indirectly contribute to these changes. As a result, there are shifts in the geographical distribution of pathogens, rates of infection, host-pathogen interactions, evolution rates, and the effectiveness of disease management, potentially leading to an increase in damaging epidemics, ultimately impacting plant health (Hunjan & Lore, 2020; Ainsworth *et al.*, 2020; Singh *et al.*, 2023). The effects of increasing CO₂ on plants, including its impact on physiological processes such as photosynthesis, respiration, water balance, nutrient absorption, response to environmental stresses, and overall growth and development, have been studied. However, it is recognized that elevated carbon dioxide levels can lead to the destabilization of agricultural ecosystems, particularly in arid and semi-arid regions in the long term.

Increase in temperature, change in precipitation pattern and yield gap

The world is involved in a very clear warming process, a process in which the increase in carbon levels and natural temperature anomalies have caused the global temperature to rise. Due to the trend of increasing temperature, the performance of agricultural products, especially the yield gap, may face multifaceted challenges in the future (Zandalinas *et al.*, 2021). An increase in temperature can cause morphological, metabolomic, physiological, and ecological disorders that lead to changes in the growth schedule and severe cases lead to plant death (Seth & Sebastian, 2024). High temperature affects the plant from germination to growth and development and affects various physiological processes such as photosynthetic functions, reproductive processes (flowering, pollination, and seed creation), and absorption and transport of water and nutrients (Evans *et al.*, 2008). An increase in temperature directly impacts various aspects of the host plant's biology. This includes phenology, the quantity, and composition of carbohydrates, nitrogen, and phenolic compounds, as well as the quantity of root and stem biomass, the size and number of leaves, stomatal density, stomatal conductance, root secretions,

and wax compounds on the leaves. All the plant's processes are regulated by enzymes and hormones, which are also influenced by temperature (Seth & Sebastian, 2024). Various research shows that by increasing the temperature by 10 degrees centigrade, the activity of enzymes and hormones doubles, but if the temperature increases too much, the action and function of hormones and enzymes will be disturbed. Also, mechanisms in high heat conditions can increase the activities of antioxidant enzymes and heat shock proteins in cell defense cycles, which causes plant energy consumption and increases the yield gap (Chen *et al.*, 2021; Seth & Sebastian, 2024).

Temperature affects most of the processes related to product quantity estimation. Where crops are grown near the upper limit of tolerable temperature, the occurrence of very hot periods can be fatal to the plant, while in cooler regions such as Europe, the increase in average annual temperature since the 1980s has increased production. Higher temperatures can have a positive effect on increasing the amount of yield gap because it increases plant phenology and reduces the time of biomass accumulation. Also, if the increase in temperature is accompanied by drought stress, it often leads to the production of smaller and more fibrous leaves, which show changes in nutritional quality, for example, a decrease in nitrogen and an increase in tannins and phenols, which the combination of these factors can increase yield gap (Seth & Sebastian, 2024). The increasing temperature affects plant yield, including extreme environmental conditions such as floods, droughts, heat waves, and strong winds. Drought, for example, can make plants more susceptible to pollution, diseases, and pests. In tropical regions, plants are sensitive to temperature changes. An increase in temperature can directly impact various aspects of plant biology, such as phenology, carbohydrate and nitrogen levels, phenolic compounds, root and stem biomass, leaf size and number, stomatal conductance, root secretions, and the composition and amount of wax on the leaves, leading to a potential increase in the yield gap (Zandalinas *et al.*, 2021; Singh *et al.*, 2023; Hunjan & Lore, 2020).

Changing precipitation patterns is one of the most obvious consequences of climate change worldwide. However, the intensity of changes varies depending on different geographical regions (Morecroft & Paterson, 2006; Wang *et al.*, 2020). For example, the predicted changes in precipitation are almost negative for most of the regions of America, Asia, and parts of Canada and Australia, while most of the regions of the European continent will experience positive changes in the form of an increase in annual precipitation (Miranda *et al.*, 2011; Yue *et al.*, 2020; Miranda *et al.*, 2009).

In general, the results of the available estimates indicate that the dry and semi-arid places of the world will become drier. This can play a huge role in increasing the yield gap. Various research shows that the areas that have more decrease in rainfall will also face more increase in temperature. The simultaneous occurrence of these two phenomena will affect many agroclimatic indicators, this issue can significantly increase the yield gap (Yue *et al.*, 2020; Miranda *et al.*, 2009; Yue *et al.*, 2016). Forecast models show that light and frequent rains will increasingly turn into heavy showers and that this change is not limited to just one month but is a global trend throughout the year, leading to heavier but less rainfall. The response of plants to these changing conditions varies dramatically. Plants in arid ecosystems typically respond to torrential rainfall less than plants in wetter environments. This sensitivity can alter the dominant vegetation types and potentially disrupt the ecosystem balance, which increases the yield gap (Miranda *et al.*, 2011; Feldman *et al.*, 2024).

Conclusion

The available evidence indicates that climate change affects weather patterns, which could lead to an increase in the yield gap of plants in the coming decades, particularly in our country. However, there have been limited studies on the national-level effects of climate change on the yield gap of plants. Given the significance of agriculture in ensuring food security and its role in the economic, political, cultural, and social aspects of society, it is increasingly important to understand the impact of climate change on the plant yield gap and to develop new sustainable management solutions to reduce these gaps. Such efforts can play a crucial role in the future of agriculture and contribute to the country's development, progress, and production growth programs.

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