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Review Article

Phenological Responses of Wheat (*Triticum Aestivum* L.) Crop to Climate Variability and Change: Review

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Abstract

Phenological data plays a vital role in crop management and decision-making processes that influence the global food system. This systematic review aims to explore how wheat (*Triticum aestivum* L.) phenology responds to variations in temperature and carbon dioxide across different growth stages, as well as the resulting impacts on nutritional quality. A growing body of global research highlights significant shifts in wheat phenology due to rising temperatures. However, findings are inconsistent some studies report an advancement of phenological stages by several days per decade, while others observe delays in the growing season, vegetative, and reproductive phases. Elevated carbon dioxide levels also influence wheat phenology, triggering both early and delayed flowering, as well as variations in elongation and maturity. Climate variability disrupts wheat's carbon metabolism, mineral uptake, and nutrient use efficiency, contributing to reductions in essential minerals such as Fe, Mg, Mn, P, S, and Zn, which carry serious health and nutritional consequences. Consequently, wheat phenology, yield, and nutritional content are all sensitive to climatic changes. To mitigate these effects, the use of wheat varieties with region-specific adaptation strategies is recommended in the face of a changing climate.

Keywords

Climate Change, Climate Variability, Carbon Dioxide, Temperature, Phenology, Wheat

1. Introduction

Phenology is the study of recurring biological events in vegetation and how these are influenced by both biotic and abiotic factors, as well as interactions among species. Monitoring vegetation phenological cycles offers valuable insights into environmental conditions such as the start and end of the growing season and can reveal shifts in ecosystem functions and species composition [1]. As a sensitive indicator of climate change, phenology plays a vital role in tracking alterations in carbon, water, and nitrogen cycles, especially within the global carbon cycle [2-4].

In agricultural contexts, crop phenology focuses on key developmental stages of crops, including emergence, greening, jointing, heading, grain filling, and maturity, as well as seasonal and cyclical patterns [5]. Accurate phenological data are essential for selecting suitable cultivation sites, optimizing management practices, and forecasting yields. Such data enable the modeling of crop growth, monitoring of developmental progress, and yield prediction [6, 7]. Phenology is also a core parameter in process-based crop models, which simulate crop development and productivity under varying environmental conditions [8]. A clear understanding of phenological timing and variability supports well-informed agri-

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cultural decision-making, leading to improved yield stability and food quality [9].

Climate is the dominant factor driving variability in global crop production, accounting for approximately one-third to two-thirds of the fluctuations in yield [10]. Each crop type has distinct stages in its growth cycle that are particularly sensitive to climatic conditions, and these critical periods can differ by region and season [11]. Among various crops, cereals are especially susceptible to the effects of climate change [7] making phenological changes a valuable indicator for evaluating climate change impacts on agricultural systems at the local scale. Key environmental factors including accumulated thermal time, atmospheric carbon dioxide concentrations, and crop management practices such as cultivar selection and the timing of sowing or transplanting play a significant role in shaping crop phenological development [12].

Ongoing global warming has significantly disrupted major crop production systems. According to the Intergovernmental Panel on Climate Change [13], the global average surface temperature between 2011 and 2020 increased by 1.09°C compared to the pre-industrial period of 1850-1900. Rising temperatures and elevated humidity levels accelerate plant development, leading to hastened wheat phenological progression [14]. Between 1981 and 2014, increases in global mean temperature contributed to a reduction in the duration of wheat's growing season including both vegetative and reproductive phases by approximately 0.08 to 0.36 days annually [15]. Additionally, from 1972 to 2013, the timing of wheat heading advanced by an average of 4.1 days per decade globally [16]. In Germany, among 78 agronomic and horticultural crops, phenological stages shifted by 3.73 to 4.31 days per 1°C increase in temperature [17]. Similarly, in China, the wheat growth period showed a negative correlation with temperature, with phenological stages advancing at an average rate of 3.8 days/°C between greening and heading, and 1.2 days/°C from heading to maturity [18, 19].

Ethiopia ranks as Africa's second-largest wheat producer after South Africa [20]. Despite this, the country imports approximately 1.8 million metric tons of wheat annually [21], underscoring the need to understand the sensitivity of domestic wheat production to climate change [22]. A study by Tufa et al. [23] projects that, under the RCP4.5 climate scenario, Ethiopia's wheat production could decline by 15.6% by the 2050s and 27.0% by the 2080s. In the Central Rift Valley, average temperatures are expected to rise by 0.12 to 0.54°C per decade, potentially shortening the crop-growing season by up to 76 days [24]. Moreover, climate change may significantly affect the phenological development of key wheat varieties such as Dandaa, Digelu, and Kakaba [25]. In resource-limited environments where soil fertility, water, and nutrients are constrained delays in phenological development can lead to notable yield reductions [24, 26, 27]. Historically, phenology has served as a crucial indicator of climate and weather shifts, especially in agricultural systems [28]. This systematic review aims to explore how elevated temperatures and increased atmospheric carbon dioxide levels influence the phenology of wheat at various developmental stages, and how these changes affect both yield and nutritional quality.

2. Crop Phenology and Climatic Factors

Crop development and yield collectively referred to as agricultural phenology are strongly influenced by weather conditions. Understanding how phenological processes respond to climate change is essential [29], as the timing and duration of key growth stages play a critical role in determining both yield and food quality. With rising global temperatures, shifts in crop phenology are becoming more pronounced, directly impacting agricultural productivity [6, 17]. Measuring these phenological shifts enables agricultural stakeholders to design adaptive strategies in response to climate variability [30]. As such, the influence of climate change on crop phenology remains a central issue in ensuring sustainable agricultural production [3]. In this context, the following discussion will examine how elevated temperatures and increased carbon dioxide concentrations affect the phenological behavior of wheat. Particular focus will be placed on the reproductive stages, yield performance, and nutritional quality of wheat in relation to these climatic factors.

2.1. Phenological Response of Wheat Crop to Rising Temperature

The timing and progression of phenological events are influenced by multiple factors, including temperature, precipitation, human interventions, vegetation growth, canopy structure, and ecological functions. However, the magnitude and nature of these impacts vary regionally. Among these factors, temperature plays a dominant role in controlling the seasonal patterns of plant development. Due to its reliability as an indicator of climate change, the relationship between rising temperatures and crop phenophases has become an area of growing research interest. Numerous studies have shown that increasing temperatures are contributing to significant shifts in crop phenology across the globe [17, 31].

Ren et al. [15] reported that global temperature variability has led to a shortening of the wheat growing season, with reductions in both vegetative and reproductive stages at rates ranging from 0.08 to 0.36 days per year. Similarly, projections by Zheng et al. [32] suggest that temperature increases between 2025 and 2050 could shorten wheat maturity by 3 to 24 days compared to the baseline period of 1961-1990. Supporting this, Rezaei et al. [16] documented a global advancement of heading dates by approximately 4.1 days per decade from 1972 to 2013. According to Sadras and Monzon [5], flowering and maturity stages accelerate by around 7 days per 1°C increase, with global temperatures rising at an estimated rate of 0.02°C annually.

Ludwig and Asseng [33] further demonstrated that a 1.7°C rise in average temperature led to wheat flowering 11 days earlier, equivalent to an advancement of 6.5 days per 1°C. Anwar et al. [27] observed that wheat at warmer sites reached flowering 103 days after sowing, compared to 120 days at cooler locations, regardless of soil type. In both Pakistan (1980-2014) and China (1981-2009), Hayat and Ahmad [7] and He et al. [34] found that a 1°C increase in air temperature above the optimal range advanced the anthesis stage by 5.3 and 3.7 days per decade, respectively, and maturity by 5.4 and 3.1 days per decade. Conversely, the sowing stage was delayed by 9.5 and 1.2 days, and the emergence stage by 1.3 days per decade in both countries, respectively.

Elevated temperatures not only shorten crop growing seasons but also accelerate developmental rates, reducing the time available for critical resource acquisition such as sunlight, water, and nutrients. This compression of growth periods, particularly in warmer climates, can adversely affect crop yields [18, 35, 36]. Craufurd and Wheeler [12] emphasized that these reductions in developmental timeframes are directly linked to declines in agricultural productivity. Consequently, numerous studies have shown that as temperatures rise, wheat phenological stages including sowing, emergence, anthesis, and maturity are shifting earlier or later at varying rates per decade, as detailed in Tables 1 and 2.

Table 1. *Earlier days per decade phenological stages of Wheat crop in different countries.*

Country	Earlier days per decade				References
	Sowing	Emergence	Anthesis	Maturity	
Pakistan	delay	delay	5.3	1.3	[7]
China	13.2	9.8	11.0	10.8	[37]
China	7.6	6.3	2.0	4.8	[38]
Spain	3.8	2.6	5.2	2.9	[36]
Australia	3.9	2.8	7.5	5.8	[39]
German	2	1.8	4.1	5.0	[16]
China	Delay	Delay	3.7	3.1	[34]
China	Delay	Delay	2.7	1.4	[19]

Table 2. *Delay days per Decade of phenological stages of Wheat crop in different countries.*

Country	Delay Days per decade				References
	Sowing	Emergence	Anthesis	Maturity	
Pakistan	9.5	1.3	earlier	earlier	[40]
Argentina	3	2.9	4.2	4.9	[41]
Romania	3.5	2.5	2.2	3.0	[42]
China	1.2	1.3	earlier	earlier	[34]
China	1.5	1.4	earlier	earlier	[19]

As illustrated in Figure 1, Wang et al. [9] reported that rising air temperatures in northwest China led to significant reductions in wheat phenological phases. Between 1981 and 2004, the durations from Sowing to Anthesis (SA), Anthesis to Maturity (AM), and Sowing to Maturity (SM) declined by 16.1, 8.2, and 12.3 days per decade, respectively marking the most pronounced trend of phenological shortening observed in the study. In contrast, Croitoru et al. [42] observed comparatively smaller shifts in crop phenological phases due to climate variability in Romania during the period 1971-2006. Similarly, findings by Hossain et al. [43] and Martínez-Núñez et al. [44] confirmed the influence of climate variability and change on crop phenology. These studies also highlighted that the magnitude of phenological changes is influenced by both seasonal conditions and geographic or agro-ecological contexts.

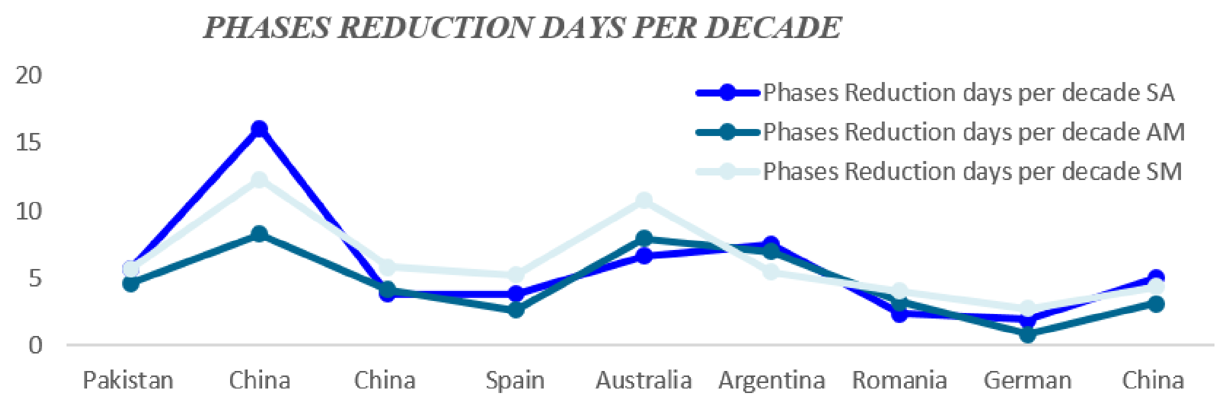

Figure 1. *Wheat crop phenological reduced days/decade in different phenophase (SA= sowing to Anthesis, AM= Anthesis to Maturity, SM= sowing to maturity stages.*

2.2. Phenological Response of Wheat Crop to Elevated Carbon Dioxide

Atmospheric carbon dioxide (CO_2) levels are projected to rise by approximately 40% from preindustrial levels, reaching around 935 ppm by the end of the 21st century [45]. This dramatic increase is expected to directly affect plant physiology and growth patterns. Elevated CO_2 can enhance photosynthetic rates [46], stimulate overall plant growth [47], and increase flowering and fruiting [48], ultimately boosting crop yields [2]. However, it also leads to a decrease in plant nutrient concentrations [49], a higher carbon-to-nitrogen (C:N) ratio [50], and altered food quality. Under such conditions, C_3 crops like wheat are predicted to see a 15% to 41% increase in productivity, while C_4 crops like maize may experience a 5% to 10% rise [51].

Specifically, in wheat, elevated CO_2 has been shown to accelerate phenological development—leading to earlier flowering and maturity [52-54]. For instance, wheat crops exposed to elevated CO_2 headed 1.2 days earlier and reached flag leaf senescence 3.5 days sooner than those grown under ambient conditions [53]. Similar findings in China indicated accelerated heading and maturity by 1.3 days each under elevated CO_2 [54]. As climate change intensifies, shifts in wheat phenology are becoming more apparent. Xiao et al. [55] reported that spring wheat's reproductive phase could shorten by 1.0 to 4.0 days under RCP4.5 and RCP8.5 scenarios, while winter wheat might experience a slight extension of 1.2 to 4.1 days. Furthermore, projections by Demelash et al. [25] suggest that under the RCP8.5 scenario, the anthesis period for the Dandaa cultivar could be shortened by up to 20 days, and by 14 days for the Digelu and Kakaba varieties. Similarly, maturity stages may advance by as much as 32, 20, and 27 days, respectively, for Dandaa, Digelu, and Kakaba during the late 21st century. These shifts underscore the pressing need to understand and anticipate how elevated CO_2 and changing climatic conditions will reshape crop development and productivity, especially for climate-sensitive staples like wheat.

Thus, rising CO_2 levels are expected to increase wheat productivity but may reduce nutritional quality due to higher C:N ratios. Elevated CO_2 accelerates wheat phenology, leading to earlier flowering and maturity, potentially shortening the growing season. These changes require adaptation in crop management, including adjusting sowing dates and selecting suitable cultivars. Understanding these impacts is essential for maintaining food security amid climate change.

2.3. Phenological Response of Wheat to Combined Effect Temperature and Carbon Dioxide

Temperature and atmospheric carbon dioxide (CO_2) concentration are two of the most critical factors influencing crop development, growth, and yield ultimately shaping global food production patterns. According to Hatfield et al. [56], elevated CO_2 levels tend to enhance biomass accumulation and increase wheat yield; however, the positive effects of CO_2 enrichment are strongly dependent on the surrounding temperature conditions. Grant et al. [57] and Kheir et al. [58] both reported that an increase in temperature ranging from 1 °C to 4 °C can reduce wheat yields by approximately 17.6%.

In contrast, elevated CO_2 concentrations can counterbalance the adverse effects of temperature by improving photosynthetic efficiency, increasing intracellular CO_2 levels, reducing water loss, and strengthening structural integrity through modifications in the basal internodes, thereby enhancing lodging resistance [59]. Field experiments by White et al. [60], using temperature free-air-controlled enhancement (T-FACE) systems, demonstrated that higher temperatures (up to 40 °C) significantly accelerated wheat heading time.

Cai et al. [61] conducted trials during 2012-2013 and found that under ambient CO_2 and temperature conditions, wheat took 159 days to develop from sowing to heading. In comparison, under combined elevated CO_2 and temperature, this growth period was reduced to 149 days. From heading to maturity, the duration remained relatively unchanged at around 30-31 days under both elevated and ambient conditions.

These highlight the complex interplay between temperature and CO_2 levels in determining wheat phenology and productivity. While elevated CO_2 may partially offset the negative impacts of rising temperatures on wheat yield, the net outcome is highly dependent on the extent of temperature stress and its timing within the crop's developmental stages. Understanding these dynamics is critical for developing resilient crop varieties and adaptive agronomic practices. In regions facing more frequent heatwaves or prolonged warm seasons, the accelerating effect of high temperatures on phenological stages could reduce the duration available for resource accumulation, ultimately lowering yield potential and grain quality. Therefore, agricultural stakeholders and policymakers must integrate climate projections into planning and decision-making, focusing on breeding climate-resilient cultivars, optimizing planting schedules, and ensuring food security in a changing climate.

2.4. Effects of Changes in Temperature on Wheat Crop Yield

High temperatures significantly impact most field crops, often leading to reduced yields [56, 62]. Wheat, in particular, is highly vulnerable to climate conditions, especially during its reproductive stage [63]. Studies indicate that even a 1°C increase in maximum temperature can result in decreased wheat yield [64, 65]. The effects of temperature on wheat are more severe than for other crops, with increasing temperatures above the optimal range causing substantial yield reductions. Cai et al. [61] found that wheat phenology is more sensitive to temperature before heading than after. While high CO_2 can slightly shorten the time to anthesis by 2 days [66], high temperatures still shorten the time to maturity, reducing the growing season. Anwar et al. [67] noted that a 1°C rise in temperature could lower wheat yields by 25%, with a combined temperature and CO_2 effect leading to a 29% reduction. However, increased CO_2 may help mitigate the negative effects of higher temperatures, enhancing wheat productivity under certain conditions [58]. Thus, the combined effect of rising temperatures and elevated CO_2 levels underscores the need for adaptive strategies to maintain wheat productivity. While CO_2 enrichment may help alleviate some temperature-induced stress, it is crucial to monitor and manage climate factors to ensure stable yields. Future agricultural planning must account for these complex interactions to safeguard food security.

Table 3. *Effects of Changes in Temperature on Wheat Crop Yield.*

Model used to simulate	Climate dataset	Yield losses (%)	References
CERES-wheat model	1980-2008	2.62-10.13	[68]
Global Gridded Crop Model Simulations.	1981-2010	6	[69]
CRU TS 2.0.	1979-2000	3-10	[70]
APSIM-N wheat v1.55	1958-2007	7	[14]
Statistical and APSIM V7.5 analysis	1982 - 2008	5.3	[71]
Multi-model ensemble	1981-2010	6	[72]
Experimental	Two years	6.9	[37]
CERES-Wheat & N-Wheat Model	1981-2010	6	[58]
Statistical Model	1980-2008	5.5	[73]
Grid-based and point-based simulations and statistical regressions	1980 - 2099	4.1 - 6.4	[74]
An ensemble of crop model simulations	1980-2008	5.5	[75]
Statistical Model	1961-2002	5.4	[76]

2.5. Effects of Elevated Carbon Dioxide on Wheat Crop Yield

The increase in temperature due to CO_2 buildup in the atmosphere leads to climate change [45, 77]. As CO_2 traps heat, it impacts plants' ability to photosynthesize, a key process for growth. Elevated CO_2 levels, however, have a positive effect on plants, promoting faster growth and higher yields by enhancing carbon absorption [78]. Research suggests that rising CO_2, in the absence of other climate changes, could benefit C_3 crops like wheat, potentially boosting future crop yields [58, 78]. Additionally, studies show that CO_2 enrichment increases photosynthesis in C_3 plants by 33-40%, while C_4 plants see a 10-15% boost [79]. This greater carbon assimilation fosters plant growth. Free-air CO_2 enrichment (FACE) experiments by Ainsworth & Long [78] has confirmed that elevated CO_2 enhances photosynthetic rates and crop yields. For instance, a FACE experiment showed a 14% yield increase for C_3 crops (wheat, rice, soybean) at 583 ppm CO_2 compared to 367 ppm CO_2 [80, 81]. Further studies by Prasad et al. [82] and Kimball [78] found that elevated CO_2 boosts photosynthesis, carbon fixation, and biomass, while reducing transpiration, leading to higher yields. Yadav et al. [83] confirmed that raising CO_2 levels increased grain yield by 25.4%, with Kimball [78] and Tao et al. [84] estimating an average yield increase of 19%, particularly higher in dry conditions. Therefore, the rise in atmospheric CO_2 levels could significantly enhance the growth and yield of C_3 crops, like wheat, by boosting photosynthesis and carbon fixation. This suggests that elevated CO_2 may mitigate some of the adverse effects of climate change, particularly in terms of crop productivity. However, the benefits of increased CO_2 are likely to be influenced by other climatic factors, such as temperature and precipitation. Thus, understanding the interactions between CO_2 and climate variables is crucial for future agricultural planning and food security.

2.6. Effect of Combined Temperature and CO_2 Changes on Wheat Crop Yield

The primary causes of climate change that impact food production globally are carbon dioxide and temperature. The key factors that influence crop development, growth, and yield are temperature and CO_2 concentration. Studies have examined the individual and combined effects of temperature increase and CO_2 concentration changes on wheat growth and yield [56]. According to Kheir et al. [58] a temperature increases of 1 ℃ to 4 ℃ results in a 17.6% reduction in wheat yield. However, enhanced yield due to elevated CO_2 concentrations may offset some of the negative temperature effects. A shorter period between crop emergence and maturity is the reason that rising temperatures negatively impact wheat crop productivity. Conversely, rising CO_2 levels may increase crop yield by enhancing photosynthesis, increasing cellular CO_2 concentrations [85], and reducing water use [86], or by improving lodging resistance through changes in the physicochemical properties of the basal internodes [69].

Anwar et al. [67] reported that the joint effects of temperature and CO_2 enrichment would lead to a 25% reduction in grain production for five genotypes of wheat. This decline would occur solely due to temperature under medium scenarios. In a study on the sensitivity of climate change, Kheir et al. [58] found that wheat yield decreased by 17.6% when temperatures rose by 1 to 4 ℃. However, higher atmospheric CO_2 levels enhanced yield, potentially offsetting some of the detrimental effects of rising temperatures. This finding indicates that the impact of higher temperatures could be alleviated and reduced by elevated CO_2 concentrations.

2.7. Effects of Rising Temperature on Wheat Crop Nutrients Contents

The timing of when plants flower and produce fruit is being affected by temperature changes. This is also impacting the overall growth process and speeding up the metabolism of plants. Research has shown that photosynthesis, the process by which plants convert sunlight into energy, is particularly sensitive to high temperatures and can be completely stopped before other plant processes are affected [39, 87]. When temperatures become too high, a key enzyme in photosynthesis called Rubisco can become inactive, which can reduce a plant's ability to absorb carbon dioxide and decrease the net rate of photosynthesis [88]. This can result in lower grain yield and quality in many wheat cultivars [89]. As a result of rising temperatures and more frequent droughts, crop yields in many regions are expected to decrease, which poses a significant threat to global food security [75]. The rapid growth brought on by increased temperatures can also lead to smaller grains with higher starch content [90].

Cereal crops like wheat are highly climate-sensitive, with the reproductive stage being the most susceptible to high temperatures [63, 64]. Maximum temperature is a critical factor affecting wheat productivity, with an increase of 1 ℃ leading to a decline in yield. Studies conducted worldwide, as shown in Table 4, indicate that temperature fluctuations can impact the development and nutrient content of wheat crops, which has significant implications for human health [91].

Table 4. *Effects of Rising Temperature on Wheat Crop Nutrient Contents.*

Effects of Increment of Temperature	References
High temperatures during crop post-anthesis can result in a significant reduction in grain-set, grain size, and milling yield.	[92]

Effects of Increment of Temperature	References
Grain protein concentration rises in response to drought stress and higher temperatures due to decreased starch accumulation.	[93]
When wheat plants were exposed to a high temperature (37/17°C) from anthesis until maturity, there was a marked reduction in the starch accumulation period (21 days earlier than the control) in the developing wheat grains compared to those subjected to a milder temperature (24/17°C).	[94]
Although increased temperature during grain filling can lead to higher protein content and more robust dough, prolonged exposure to high temperatures (up to 30°C) or sudden heat shocks (above 30°C) can negatively impact the grain's composition, reducing its end-use properties like dough strength, extensibility, and loaf volume.	[95]
Under high temperatures during the grain filling phase, protein content is observed to increase	[96]
At temperatures above 30°C, the rate of starch accumulation slows, however the rate of protein accumulation remains substantially unaltered, resulting in greater grain protein content.	[97, 98]
Despite the fact that grain protein quantity increases at high temperatures, the composition and functional qualities of both starch and protein change.	[90, 97, 99 100]
Glutenin deficiency caused by post-anthesis heat stress resulted in increased dough strength.	[96]
When temperatures are high, the amount of starch in grain can decrease by up to one-third of the total starch found in the endosperm, which is caused by a decline in the effectiveness of enzymes that are involved in the production of starch.	[101]
Under heat stress, starch production in wheat grain decreased, but total soluble sugar and protein increased.	[102]
Under heat stress, there is no discernible influence on protein concentration.	[103]
Heat stress has a substantial impact on grain setting, duration, pace, quality, and, ultimately, grain production.	[104]
Exposure to high temperature stress reduced grain yield and weight while increasing grain protein content.	[9, 84]
A significant reduction in starch can result in a reduction in grain weight and a comparably big rise in grain protein content.	[99, 105]
The overabundance of heat can hinder the performance of enzymes found in plant chlorophyll, which joins light energy and water to produce carbohydrates and energy crucial for seed development.	[106]
Rising temperatures can expedite the maturation of wheat, abbreviating the period of grain filling. Consequently, the weight of the grain diminishes, the nitrogen content increases, and the protein content decreases.	[105]
The high-temperature stress led to a decrease in total starch content, as well as in the activities of nitrate reductase and glutamine synthetase, grain protein production, and globulin content. Additionally, it led to a decrease in glutenin, gliadin, and albumin content, while increasing cysteine and methionine content.	[84]

2.8. Effects of Elevated Carbon Dioxide on Wheat Crop Nutrients Contents

The effect of elevated CO_2 on plants' ability to photosynthesize is well-established, as CO_2 is essential for plants to absorb carbon. Elevated CO_2 levels lead to increased carbon absorption, growth, yield, and C content in plants [107, 108]. However, this increased productivity can also result in reduced tissue nutrient concentration in wheat, particularly in nitrogen, leading to lower grain protein content and reduced nutritional quality of food crops [109, 91]. Additionally, elevated CO_2 levels can result in lower concentrations of minerals such as Zn and Fe in C_3 grains [110]. Furthermore, concentrations of grain protein, Fe, Zn, S and Ca were significantly reduced at elevated CO_2 (550 ppm) compared to the ambient 384 ppm [111]. Aranjuelo et al. [112] also reported that an increment in CO_2 from (400µmol/mol^{-1}) to elevated (700µmol/mol^{-1}) increased wheat grain yields, but decreased the accumulation of storage proteins and the concentration of minerals in wheat grain. Moreover, Loladze [113] pointed out that elevated CO_2 levels are likely to induce a shift in the stoichiometry of plants, promoting higher concentrations of C and lower concentrations of other nutrients such as N, Fe, and Zn, with important implications for human nutrition. Consequently, a decrease in grain protein content may have significant economic and health effects, eventually causing human populations to experience hidden hunger [92]. The impacts of elevated CO_2 levels on the nutritional characteristics of wheat crops, including their protein, mineral, and vitamin contents, are shown in Table 5.

Table 5. Effects of Elevated Carbon Dioxide on Wheat Crop Nutrient Contents.

Effects of Elevated Carbon dioxide	References
Wheat yield can rise by up to 36% when exposed to increased CO_2, but grain protein concentration falls and a shift in composition results in lower functional characteristics.	[114]
Elevated CO_2 concentration increases the overall amount of protein in grain but decreases its concentration.	[91, 115]
Under [eCO_2], grain Zn, Fe, Ca, and S concentrations were decreased.	[112, 116]
Total grain protein concentration dropped by 7.4% in a short period of time. Protein and amino acid composition changed when CO_2 levels increased; manganese, iron, cadmium, and silicon concentrations fell while potassium, molybdenum, and lead concentrations increased.	[116]
Most minerals (Ca, Cd, Cu, Fe, Mg, Mn, P, S, and Zn) declined, but B and Na were unaffected and K was slightly enhanced (2%).	[91]
While ribose-5-P considerably rose by 34.2%, the glower level of the phosphorylated sugar gluconate-6-P decreased by 7.0%.	[116]
The most significant decreases were observed for the nutrients N, Fe, S, Zn, and Mg.	[91]
Even without yield stimulation, a drop in N uptake under e[CO_2] can be caused by both a decrease in transpiration-driven mass flow and decreased N acquisition processes.	[117]
The concentrations of Some important mineral nutrients (Fe and Zn) have decreased.	[115]
Wheat grown under increased atmospheric CO_2 concentrations (550 ppm) lowered iron concentrations by4-10%	[115, 118]
Zinc and protein levels dropped as eCO_2 increased	[119, 120]
Proteins, amino acids, and N are all reduced by eCO_2, which also changes the make-up of gluten. While no difference was noted in the build-up of starch, it was also found that the concentration of certain minerals (Ca, Cd, Cu, Fe, Mg, Mn, P, S, and Zn) was significantly reduced.	[91]
The reduction of protein concentrations that occurred due to elevated carbon dioxide was often attributed to a dilution effect	[50, 121]

3. Conclusion

The phenology of crops plays a vital role in how plants adapt to climate change and is a key factor in global food security. Factors like rising temperatures, higher carbon dioxide levels, and changing rainfall patterns are affecting cereal crop production, particularly wheat. This review examines the influence of climate change on wheat's phenology, noting that increasing temperatures are causing phenological events to occur earlier, which shortens the time available for the crop to assimilate CO_2, ultimately leading to reduced yields. Climate change's impact on wheat goes beyond phenology; it also affects the crop's ability to absorb essential minerals such as iron, magnesium, manganese, phosphorus, sulfur, and zinc, with significant consequences for health and nutrition. Understanding the timing and variability of phenophases each year can improve crop management, resulting in higher, more stable yields with enhanced nutritional quality. Future research should focus on developing predictive models that integrate climate variables with phenological and nutritional responses to guide adaptive breeding and management strategies under changing climatic conditions.

Abbreviations

SA	Sowing to Anthesis
AM	Anthesis to Maturity
SM	Sowing to Maturity
CERES-wheat model	Crop Environment Resource Synthesis for Wheat
CRU TS 2.0.	Climatic Research Unit Time-Series Version 2.0
APSIM V7.5 analysis	Agricultural Production Systems sIMulator Version 7.5

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Tesfaye Bogale: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing original draft

Sileshi Degefa: Conceptualization, Supervision, Validation Writing, review & editing

Gemedo Dalle: Conceptualization, Supervision, Validation Writing, review & editing

Ethical Approval and Consent to Participate

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Not applicable.

Consent for Publication

Not applicable.

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The authors declares that We can submit the required data at all times. The data sets used will be available from the authors up on request.

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References

[1] Leith, H. (1974). Phenology and Seasonality Modelling; Springer Verlag. s.n.. Springer Verlag, New York, NY, US.

[2] Boko, M., Niang, I., Nyong, A., Vogel, A., Githeko, A., Medany, M.,... & Yanda, P. Z. (2007). Africa climate change 2007: Impacts, adaptation and vulnerability: Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change.

[3] Xiao, D., Moiwo, J. P., Tao, F., Yang, Y., Shen, Y., Xu, Q.,... & Liu, F. (2015). Spatiotemporal variability of winter wheat phenology in response to weather and climate variability in China. *Mitigation and Adaptation Strategies for Global Change*, *20*, 1191-1202.

[4] Adole, T., Dash, J., & Atkinson, P. M. (2016). A systematic review of vegetation phenology in Africa. *Ecological Informatics*, *34*, 117-128.

[5] Sadras, V. O., & Monzon, J. P. (2006). Modelled wheat phenology captures rising temperature trends: Shortened time to flowering and maturity in Australia and Argentina. *Field crops research*, *99*(2-3), 136-146.

[6] Tao, J. B., Wu, W. B., Yong, Z. H. O. U., Yu, W. A. N. G., & Jiang, Y. (2017). Mapping winter wheat using phenological feature of peak before winter on the North China Plain based on time-series MODIS data. *Journal of Integrative Agriculture*, *16*(2), 348-359.

[7] Hayat, R., & Ahmad, S. (2019). Biochemical, physiological and agronomic response of wheat to changing climate of rainfed areas of Pakistan. *Pak. J. Bot*, *51*(2), 535-551.

[8] Liu, Y., Qin, Y., Ge, Q., Dai, J., & Chen, Q. (2017). Reponses and sensitivities of maize phenology to climate change from 1981 to 2009 in Henan Province, China. *Journal of Geographical Sciences*, *27*, 1072-1084.

[9] Wang, H. L., Gan, Y. T., Wang, R. Y., Niu, J. Y., Zhao, H., Yang, Q. G., & Li, G. C. (2008). Phenological trends in winter wheat and spring cotton in response to climate changes in northwest China. *Agricultural and Forest Meteorology*, *148*(8-9), 1242-1251.

[10] Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature communications*, *6*(1), 5989.

[11] Dreccer, M. F., Fainges, J., Whish, J., Ogbonnaya, F. C., & Sadras, V. O. (2018). Comparison of sensitive stages of wheat, barley, canola, chickpea and field pea to temperature and water stress across Australia. *Agricultural and Forest Meteorology*, *248*, 275-294.

[12] Craufurd, P. Q., & Wheeler, T. R. (2009). Climate change and the flowering time of annual crops. *Journal of Experimental botany*, *60*(9), 2529-2539.

[13] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, https://doi.org/10.1017/9781009157896.001

[14] Asseng, S., Foster, I. A. N., & Turner, N. C. (2011). The impact of temperature variability on wheat yields. *Global Change Biology*, *17*(2), 997-1012.

[15] Ren, S., Qin, Q., & Ren, H. (2019). Contrasting wheat phenological responses to climate change in global scale. *Science of the Total Environment*, *665*, 620-631.

[16] Rezaei, E. E., Siebert, S., Hüging, H., & Ewert, F. (2018). Climate change effect on wheat phenology depends on cultivar change. *Scientific reports*, *8*(1), 4891.

[17] Estrella, N., Sparks, T. H., & Menzel, A. (2007). Trends and temperature response in the phenology of crops in Germany. *Global Change Biology*, *13*(8), 1737-1747.

[18] Tao, F., Zhang, S., & Zhang, Z. (2012). Spatiotemporal changes of wheat phenology in China under the effects of temperature, day length and cultivar thermal characteristics. *European Journal of Agronomy*, *43*, 201-212.

[19] Xiao, D., Tao, F., Liu, Y., Shi, W., Wang, M., Liu, F.,... & Zhu, Z. (2013). Observed changes in winter wheat phenology in the North China Plain for 1981-2009. *International Journal of Biometeorology*, *57*, 275-285.

[20] Demeke, M., & Di Marcantonio, F. (2019). Analysis of incentives and disincentives for wheat in Ethiopia. *Gates Open Res*, *3*(419), 419.

[21] World Bank. (2018). Poverty and shared prosperity 2018: Piecing together the poverty puzzl.

[22] Haileselassie, B., Habte, D., Haileselassie, M., & Gebremeskel, G. (2014). Effects of mineral nitrogen and phosphorus fertilizers on yield and nutrient utilization of bread wheat (Tritcum aestivum) on the sandy soils of Hawzen District, Northern Ethiopia. *Agriculture, Forestry and Fisheries*, *3*(3), 189-198.

[23] Tufa, Z. D., Getnet, M., & Nigatu, L. (2018). Modeling Impacts of Climate Change on Bread Wheat (Triticum Aestivum l.) Productivity in Bale.

[24] Kassie, B. T., Rötter, R. P., Hengsdijk, H., Asseng, S., Van Ittersum, M. K., Kahiluoto, H., & Van Keulen, H. (2014). Climate variability and change in the Central Rift Valley of Ethiopia: challenges for rainfed crop production. *The Journal of Agricultural Science*, *152*(1), 58-74.

[25] Demelash, T., Amou, M., Gyilbag, A., Tesfay, G., & Xu, Y. (2021). Adaptation potential of current wheat cultivars and planting dates under the changing climate in Ethiopia. *Agronomy*, *12*(1), 37.

[26] Lobell, D. B., Sibley, A., & Ivan Ortiz-Monasterio, J. (2012). Extreme heat effects on wheat senescence in India. *Nature Climate Change*, *2*(3), 186-189.

[27] Anwar, M. R., Li Liu, D., Farquharson, R., Macadam, I., Abadi, A., Finlayson, J.,... & Ramilan, T. (2015). Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia. *Agricultural Systems*, *132*, 133-144.

[28] Schwartz, M. D. (Ed.). (2003). *Phenology: an integrative environmental science* (Vol. 132). Dordrecht: Kluwer Academic Publishers.

[29] Xiao, W., Xu, S., & He, T. (2021). Mapping paddy rice with sentinel-1/2 and phenology-, object-based algorithm—A implementation in Hangjiahu plain in China using gee platform. *Remote Sensing*, *13*(5), 990.

[30] Mo, X. G., Hu, S., Lin, Z. H., Liu, S. X., & Xia, J. (2017). Impacts of climate change on agricultural water resources and adaptation on the North China Plain. *Advances in Climate Change Research*, *8*(2), 93-98.

[31] Chmielewski, F. M., Müller, A., & Bruns, E. (2004). Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. *Agricultural and Forest Meteorology*, *121*(1-2), 69-78.

[32] Zheng, Z., Cai, H., Wang, Z., & Wang, X. (2020). Simulation of climate change impacts on phenology and production of winter wheat in Northwestern China using CERES-wheat model. *Atmosphere*, *11*(7), 681.

[33] Ludwig, F., & Asseng, S. (2010). Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. *Agricultural Systems*, *103*(3), 127-136.

[34] He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W.,... & Yu, Q. (2015). Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agricultural and Forest Meteorology*, *200*, 135-143.

[35] Liu, Y., Chen, Q., Ge, Q., Dai, J., Qin, Y., Dai, L.,... & Chen, J. (2018). Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. *Agricultural and Forest Meteorology*, *248*, 518-526.

[36] Oteros, J., García-Mozo, H., Botey, R., Mestre, A., & Galán, C. (2015). Variations in cereal crop phenology in Spain over the last twenty-six years (1986-2012). *Climatic Change*, *130*, 545-558.

[37] Wang, J., Vanga, S. K., Saxena, R., Orsat, V., & Raghavan, V. (2018). Effect of climate change on the yield of cereal crops: A review. *Climate*, *6*(2), 41.

[38] Li, Z., Yang, P., Tang, H., Wu, W., Yin, H., Liu, Z., & Zhang, L. (2014). Response of maize phenology to climate warming in Northeast China between 1990 and 2012. *Regional Environmental Change*, *14*, 39-48.

[39] Luo, Q., O'Leary, G., Cleverly, J., & Eamus, D. (2018). Effectiveness of time of sowing and cultivar choice for managing climate change: wheat crop phenology and water use efficiency. *International journal of biometeorology*, *62*, 1049-1061.

[40] Ahmed, M., Aslam, M. A., Fayyaz-Ul, H., Hayat, R. & Ahmad, S. (2019). Biochemical, physiological and agronomic response of wheat to changing climate of rainfed Pakistan. Pak. J. Bot 51, 535-551.

[41] Sadras, V. O. & Monzon, J. P. (2006). Modelled wheat phenology captures rising temperature trends: shortened time to fowering and maturity in Australia and Argentina. Field Crops Res. 99, 136-146. https://doi.org/10.1016/j.fcr.2006.04.003

[42] Croitoru, A. E., Holobaca, I. H., Lazar, C., Moldovan, F. & Imbroane, A. (2012). Air temperature trend and the impact on winter wheat phenology in Romania. Clim. Change 111, 393-410.

[43] Hossain, A., da Silva Teixeira, J. A., Lozovskaya, M. V. & Zvolinsky, V. P. (2012). High temperature combined with drought affect rainfed spring wheat and barley in SouthEastern Russia: I. Phenology and growth. Saudi J. Biol. Sci. 19, 473-487.

[44] Martínez-Núñez, M. et al. (2019). phenological growth stages of different amaranth species grown in restricted spaces based in BBCH code. South African J. Bot. 124, 436-443.

[45] Field, C. B., Barros, V. R., Mastrandrea, M. D., Mach, K. J., Abdrabo, M. A., Adger, W. N.,... & Yohe, G. W. (2015). Summary for policymakers. In *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1-32). Cambridge University Press.

[46] Srivastava, A. C., Khanna, Y. P., Meena, R. C., Pal, M., & Sengupta, U. K. (2002). Diurnal changes in photosynthesis, sugars, and nitrogen of wheat and mungbean grown under elevated CO_2 concentration. *Photosynthetica*, *40*, 221-225.

[47] Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, *408*(6809), 184-187.

[48] Springer, C. J., & Ward, J. K. (2007). Flowering time and elevated atmospheric CO_2. *New Phytologist*, *176*(2), 243-255.

[49] Manderscheid, R., Bender, J., Jäger, H. J., & Weigel, H. J. (1995). Effects of season long CO_2 enrichment on cereals. II. Nutrient concentrations and grain quality. *Agriculture, ecosystems & environment*, *54*(3), 175-185.

[50] Gifford, R. M., Barrett, D. J., & Lutze, J. L. (2000). The effects of elevated [CO_2] on the C: N and C: P mass ratios of plant tissues. *Plant and Soil*, *224*, 1-14.

[51] Mera, R. J., Niyogi, D., Buol, G. S., Wilkerson, G. G., & Semazzi, F. H. (2006). Potential individual versus simultaneous climate change effects on soybean (C3) and maize (C4) crops: An agrotechnology model based study. *Global and Planetary Change*, *54*(1-2), 163-182.

[52] Padhan, B. K., Sathee, L., Meena, H. S., Adavi, S. B., Jha, S. K., & Chinnusamy, V. (2020). CO_2 Elevation accelerates phenology and alters carbon/nitrogen metabolism vis-à-vis ROS abundance in bread wheat. *Frontiers in Plant Science*, 1061.

[53] Maphosa, L., Fitzgerald, G. J., Panozzo, J., Partington, D., Walker, C., & Kant, S. (2019). Genotypic response of wheat under semi-arid conditions showed no specific responsive traits when grown under elevated CO_2. *Plant Production Science*, *22*(3), 333-344.

[54] Yang, L. X., Wang, Y. L., Li, S. F., Huang, J. Y., Dong, G. C., Zhu, J. G.,... & Han, Y. (2007). Effects of free-air CO_2 enrichment (FACE) on dry matter production and allocation in wheat. *Ying Yong Sheng tai xue bao= The Journal of Applied Ecology*, *18*(2), 339-346.

[55] Xiao, D., Bai, H., & Liu, D. L. (2018). Impact of future climate change on wheat production: a simulated case for China's wheat system. *Sustainability*, *10*(4), 1277.

[56] Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D.,... & Wolfe, D. (2011). Climate impacts on agriculture: implications for crop production. *Agronomy journal*, *103*(2), 351-370.

[57] Grant, R. F., Kimball, B. A., Conley, M. M., White, J. W., Wall, G. W., & Ottman, M. J. (2011). Controlled warming effects on wheat growth and yield: field measurements and modeling. *Agronomy Journal*, *103*(6), 1742-1754.

[58] Kheir, A. M., El Baroudy, A., Aiad, M. A., Zoghdan, M. G., Abd El-Aziz, M. A., Ali, M. G., & Fullen, M. A. (2019). Impacts of rising temperature, carbon dioxide concentration and sea level on wheat production in North Nile delta. *Science of The Total Environment*, *651*, 3161-3173.

[59] Khan, S., Anwar, S., Kuai, J., Ullah, S., Fahad, S., & Zhou, G. (2017). Optimization of nitrogen rate and planting density for improving yield, nitrogen use efficiency, and lodging resistance in oilseed rape. *Frontiers in Plant Science*, *8*, 532.

[60] White, J. W., Kimball, B. A., Wall, G. W., Ottman, M. J., & Hunt, L. A. (2011). Responses of time of anthesis and maturity to sowing dates and infrared warming in spring wheat. *Field Crops Research*, *124*(2), 213-222.

[61] Cai, C., Yin, X., He, S., Jiang, W., Si, C., Struik, P. C.,... & Pan, G. (2016). Responses of wheat and rice to factorial combinations of ambient and elevated CO_2 and temperature in FACE experiments. *Global change biology*, *22*(2), 856-874.

[62] Prasad, P. V., Bheemanahalli, R., & Jagadish, S. K. (2017). Field crops and the fear of heat stress—opportunities, challenges and future directions. *Field Crops Research*, *200*, 114-121.

[63] Prasad, P. V. V., Djanaguiraman, M., Perumal, R., & Ciampitti, I. A. (2015). Impact of high temperature stress on floret fertility and individual grain weight of grain sorghum: sensitive stages and thresholds for temperature and duration. *Frontiers in Plant Science*, *6*, 820.

[64] Jha, B., & Tripathi, A. (2011). Isn't climate change affecting wheat productivity in India?. *Indian Journal of Agricultural Economics*, *66*(3).

[65] Kalra, N., Chakraborty, D., Sharma, A., Rai, H. K., Jolly, M., Chander, S.,... & Sehgal, M. (2008). Effect of increasing temperature on yield of some winter crops in northwest India. *Current science*, 82-88.

[66] O'Leary, G. J., Christy, B., Nuttall, J., Huth, N., Cammarano, D., Stöckle, C.,... & Asseng, S. (2015). Response of wheat growth, grain yield and water use to elevated CO_2 under a Free-Air CO_2 Enrichment (FACE) experiment and modelling in a semi-arid environment. *Global change biology*, *21*(7), 2670-2686.

[67] Anwar, J. A. V. E. D., Khan, S. B., Rasul, I. J. A. Z., Zulkiffal, M. U. H. A. M. M. A. D., & Hussain, M. U. J. A. H. I. D. (2007). Effect of sowing dates on yield and yield components in wheat using stability analysis. *Int. J. Agric. Biol*, *9*(1), 129-132.

[68] Liu, Y., Li, N., Zhang, Z., Huang, C., Chen, X., & Wang, F. (2020). The central trend in crop yields under climate change in China: A systematic review. *Science of the Total Environment*, *704*, 135355.

[69] Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., … Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, *114*(35).

[70] You, L., Rosegrant, M. W., Wood, S., & Sun, D. (2009). Impact of growing season temperature on wheat productivity in China. *Agricultural and Forest Meteorology*, *149*(6-7), 1009-1014.

[71] Innes, P. J., Tan, D. K. Y., Van Ogtrop, F., & Amthor, J. S. (2015). Effects of high-temperature episodes on wheat yields in New South Wales, Australia. *Agricultural and Forest Meteorology*, *208*, 95-107.

[72] Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D.,... & Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature climate change*, *5*(2), 143-147.

[73] Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, *333*(6042), 616-620.

[74] Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D. B.,... & Zhu, Y. (2016). Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, *6*(12), 1130-1136.

[75] Lobell, D. B., Thau, D., Seifert, C., Engle, E., & Little, B. (2015). A scalable satellite-based crop yield mapper. *Remote Sensing of Environment*, *164*, 324-333.

[76] Lobell, D. B., & Field, C. B. (2007). Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental research letters*, *2*(1), 014002.

[77] Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S.,... & Zhou, B. (2021). Climate change 2021: the physical science basis. *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, *2*.

[78] Ainsworth, E. A., & Long, S. P. (2005). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New phytologist*, *165*(2), 351-372.

[79] Kimball, B. A. (2016). Crop responses to elevated CO_2 and interactions with H_2O, N, and temperature. *Current opinion in plant biology*, *31*, 36-43.

[80] Boote, K. J., Allen, L. H., Prasad, P. V., Baker, J. T., Gesch, R. W., Snyder, A. M.,... & Thomas, J. M. (2005). Elevated temperature and CO_2 impacts on pollination, reproductive growth, and yield of several globally important crops. *Journal of Agricultural Meteorology*, *60*(5), 469-474.

[81] Ainsworth, E. A. (2008). Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. *Global Change Biology*, *14*(7), 1642-1650.

[82] Prasad, P. V., Allen Jr, L. H., & Boote, K. J. (2005). Crop responses to elevated carbon dioxide and interaction with temperature: grain legumes.

[83] Yadav, A. N., Kour, D., Kaur, T., Devi, R., & Yadav, N. (2020). Functional annotation of agriculturally important fungi for crop protection: current research and future challenges. *Agriculturally important fungi for sustainable agriculture: volume 2: functional annotation for crop protection*, 347-356.

[84] Blumenthal, Z., Chang, X., Wang, D., Wang, Y., Ma, S., Yang, Y., & Zhao, G. (2018). Effects of sulfur fertilization and short-term high temperature on wheat grain production and wheat flour proteins. *The Crop Journal*, *6*(4), 413-425.

[85] Asseng, S., Jamieson, P. D., Kimball, B., Pinter, P., Sayre, K., Bowden, J. W., & Howden, S. M. (2004). Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO_2. *Field Crops Research*, *85*(2-3), 85-102.

[86] Deryng, D., Elliott, J., Folberth, C., Müller, C., Pugh, T. A., Boote, K. J.,... & Rosenzweig, C. (2016). Regional disparities in the beneficial effects of rising CO_2 concentrations on crop water productivity. *Nature Climate Change*, *6*(8), 786-790.

[87] Surendran, U., Raja, P., Jayakumar, M., & Subramoniam, S. R. (2021). Use of efficient water saving techniques for production of rice in India under climate change scenario: A critical review. *Journal of Cleaner Production*, *309*, 127272.

[88] Ashraf, M. H. P. J. C., & Harris, P. J. (2013). Photosynthesis under stressful environments: An overview. *Photosynthetica*, *51*, 163-190.

[89] Tomás, D., Coelho, L. P., Rodrigues, J. C., Viegas, W., & Silva, M. (2020). Assessment of four Portuguese wheat landrace diversity to cope with global warming. *Frontiers in Plant Science*, *11*, 594977.

[90] Farooq, M., Bramley, H., Palta, J. A., & Siddique, K. H. (2011). Heat stress in wheat during reproductive and grain-filling phases. *Critical Reviews in Plant Sciences*, *30*(6), 491-507.

[91] Broberg, M. C., Högy, P., & Pleijel, H. (2017). CO_2-induced changes in wheat grain composition: meta-analysis and response functions. *Agronomy*, *7*(2), 32.

[92] Nuttall, J. G., O'leary, G. J., Panozzo, J. F., Walker, C. K., Barlow, K. M., & Fitzgerald, G. J. (2017). Models of grain quality in wheat—A review. *Field crops research*, *202*, 136-145.

[93] Triboi, E., Martre, P., Girousse, C., Ravel, C., & Triboi-Blondel, A. M. (2006). Unravelling environmental and genetic relationships between grain yield and nitrogen concentration for wheat. *European Journal of Agronomy*, *25*(2), 108-118.

[94] Hurkman, W. J., McCue, K. F., Altenbach, S. B., Korn, A., Tanaka, C. K., Kothari, K. M.,... & DuPont, F. M. (2003). Effect of temperature on expression of genes encoding enzymes for starch biosynthesis in developing wheat endosperm. *Plant Science*, *164*(5), 873-881.

[95] Wardlaw, I. F., & Wrigley, C. W. (1994). Heat tolerance in temperate cereals: an overview. *Functional Plant Biology*, *21*(6), 695-703.

[96] Panozzo, J. F., & Eagles, H. A. (2000). Cultivar and environmental effects on quality characters in wheat. II. Protein. *Australian Journal of Agricultural Research*, *51*(5), 629-636.

[97] Jenner, C. F. (1994). Starch synthesis in the kernel of wheat under high temperature conditions. *Functional Plant Biology*, *21*(6), 791-806.

[98] Altenbach, S. B., DuPont, F. M., Kothari, K. M., Chan, R., Johnson, E. L., & Lieu, D. (2003). Temperature, water and fertilizer influence the timing of key events during grain development in a US spring wheat. *Journal of Cereal Science*, *37*(1), 9-20.

[99] Blumenthal, C. S., Barlow, E. W. R., & Wrigley, C. W. (1993). Growth environment and wheat quality: the effect of heat stress on dough properties and gluten proteins. *Journal of Cereal Science*, *18*(1), 3-21.

[100] Corbellini, M., Canevar, M. G., Mazza, L., Ciaffi, M., Lafiandra, D., & Borghi, B. (1997). Effect of the duration and intensity of heat during grain filling on dry matter and protein accumulation, technological quality and protein composition in bread and durum wheat. *Functional Plant Biology*, *24*(2), 245-260.

[101] Liu, P., Guo, W., Jiang, Z., Pu, H., Feng, C., Zhu, X.,... & Little, C. R. (2011). Effects of high temperature after anthesis on starch granules in grains of wheat (Triticum aestivum L.). *The Journal of Agricultural Science*, *149*(2), 159-169.

[102] Asthir, B., & Bhatia, S. (2014). In vivo studies on artificial induction of thermotolerance to detached panicles of wheat (Triticum aestivum L) cultivars under heat stress. *Journal of Food Science and Technology*, *51*, 118-123.

[103] Lizana, X. C., & Calderini, D. F. (2013). Yield and grain quality of wheat in response to increased temperatures at key periods for grain number and grain weight determination: considerations for the climatic change scenarios of Chile. *The Journal of Agricultural Science*, *151*(2), 209-221.

[104] Poudel, P. B., & Poudel, M. R. (2020). Heat stress effects and tolerance in wheat: A review. *J. Biol. Today's World*, *9*(3), 1-6.

[105] Akter, N., & Rafiqul Islam, M. (2017). Heat stress effects and management in wheat. A review. *Agronomy for sustainable development*, *37*, 1-17.

[106] Wahid, A., Gelani, S., Ashraf, M., & Foolad, M. R. (2007). Heat tolerance in plants: an overview. *Environmental and experimental botany*, *61*(3), 199-223.

[107] Ainsworth, E. A., & Long, S. P. (2021). 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, *27*(1), 27-49.

[108] Ben Mariem, S., Soba, D., Zhou, B., Loladze, I., Morales, F., & Aranjuelo, I. (2021). Climate change, crop yields, and grain quality of C3 cereals: A meta-analysis of [CO_2], temperature, and drought effects. *Plants*, *10*(6), 1052.

[109] Högy, P., Keck, M., Niehaus, K., Franzaring, J., & Fangmeier, A. (2010). Effects of atmospheric CO_2 enrichment on biomass, yield and low molecular weight metabolites in wheat grain. *Journal of Cereal Science*, *52*(2), 215-220.

[110] Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D.,... & Huybers, P. (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annual review of public health*, *38*, 259-277.

[111] Fernando, N., Panozzo, J., Tausz, M., Norton, R., Fitzgerald, G., & Seneweera, S. (2012). Rising atmospheric CO_2 concentration affects mineral nutrient and protein concentration of wheat grain. *Food Chemistry*, *133*(4), 1307-1311.

[112] Aranjuelo, I., Sanz-Sáez, Á., Jauregui, I., Irigoyen, J. J., Araus, J. L., Sánchez-Díaz, M., & Erice, G. (2013). Harvest index, a parameter conditioning responsiveness of wheat plants to elevated CO_2. *Journal of Experimental Botany*, *64*(7), 1879-1892.

[113] Loladze, I. (2002). Rising atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry? *Trends in Ecology & Evolution*, *17*(10), 457-461.

[114] Högy, P., & Fangmeier, A. (2008). Effects of elevated atmospheric CO_2 on grain quality of wheat. *Journal of Cereal Science*, *48*(3), 580-591.

[115] Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. D., Bloom, A. J.,... & Usui, Y. (2014). Increasing CO_2 threatens human nutrition. *Nature*, *510*(7503), 139-142.

[116] Högy, P., Wieser, H., Köhler, P., Schwadorf, K., Breuer, J., Franzaring, J.,... & Fangmeier, A. (2009). Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO_2 enrichment experiment. *Plant Biology, 11*, 60-69.

[117] Mcgrath, J. M., & Lobell, D. B. (2013). Reduction of transpiration and altered nutrient allocation contribute to nutrient decline of crops grown in elevated CO_2 concentrations. *Plant, Cell & Environment*, *36*(3), 697-705.

[118] Smith, M. R., Golden, C. D., & Myers, S. S. (2017). Potential rise in iron Wang deficiency due to future anthropogenic carbon dioxide emissions. *GeoHealth*, *1*(6), 248-257.

[119] Myers, S. S., Wessells, K. R., Kloog, I., Zanobetti, A., & Schwartz, J. (2015). Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study. *The Lancet Global Health*, *3*(10), e639-e645.

[120] Medek, D. E., Schwartz, J., & Myers, S. S. (2017). Estimated effects of future atmospheric CO_2 concentrations on protein intake and the risk of protein deficiency by country and region. *Environmental Health Perspectives*, *125*(8), 087002.

[121] Fernando, N., Panozzo, J., Tausz, M., Norton, R. M., Neumann, N., Fitzgerald, G. J., & Seneweera, S. (2014). Elevated CO_2 alters grain quality of two bread wheat cultivars grown under different environmental conditions. *Agriculture, Ecosystems & Environment*, *185*, 24-33.