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Review Article

Crop Physiology and Food Quality as Influenced by the Changing Climate: A Review Article

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Abstract

Before some decades, the gaseous composition of earth's atmosphere is undergoing a significant change, largely through increased greenhouse gases emissions from energy, industry and agricultural sectors; widespread deforestation as well as fast changes in land use and land management practices. These anthropogenic activities are resulting in an increased emission of radioactively active gases, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), popularly known as the 'greenhouse gases' (GHGs). These greenhouse gases trap the outgoing infrared radiations from the earth's surface and thus raise the temperature of the atmosphere. The global mean annual temperature at the end of the 20th century, as a result of GHG accumulation in the atmosphere, has increased by 0.4-0.7℃ above that recorded at the end of the 19th century. The past 50 years have shown an increasing trend in temperature at 0.13℃ / decade, while the rise in temperature during the past one and half decades has been much higher. The changing climate also has an impact on crop physiology, including photosynthesis, nutrient absorption, partition to grain yield and accumulation of biomass of the plants. Food quality also affected due to elevated CO_2 and temperature. Therefore, economically viable and culturally acceptable adaptation strategies have to be developed and implemented. Farmers apply drought tolerant varieties, sowing time, nutrient use efficiency and other methods to alleviate the climate change challenges. Furthermore, the transfer of knowledge as well as access to social, economic, institutional, and technical resources need to be provided and integrated within the existing resources of farmers.

Keywords

Crop Physiology, Greenhouse Gases, Elevated Carbon Dioxide, Protein Denature

1. Introduction

Global atmospheric carbon dioxide concentration (CO_2) has increased from 270 to 401 ppm since the industrial revolution before 200 years ago and the average global temperatures have risen by 0.85℃, with the most pronounced effects occurring near the poles. By the end of this century, (CO_2) is expected to reach at least 700 ppm, and global temperatures are projected to raise by 4℃ or more based on greenhouse gas scenarios [10]. Precipitation regimes also are expected to shift on a regional scale as the hydrologic cycle intensifies, resulting in greater extremes in dry versus wet conditions [15]. Such changes already are having profound impacts on the physiological functioning of plants that scale up to influence interactions between plants and other organisms and ecosystems as a whole.

Due to rapid climate change, plants have become increasingly exposed to novel environmental conditions that are

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outside of their physiological limits and beyond the range to which they are adapted [30]. Plant migration may not keep pace with the unprecedented rate of current climate change; therefore, rapid evolutionary responses may be the major process by which plants persist in the future [6]. In addition, although plants may have evolved physiological plasticity that produces a fitness advantage in novel environments, climate change may be as extreme as to push plants beyond tolerance ranges even in the most plastic of genotypes [1].

Climate change can have a considerable impact on agricultural production, especially if the amount and distribution of rainfall changes. Rising temperatures and elevated atmospheric CO_2 concentrations, increases in ozone concentration and reduced radiation reaching the earth will affect agricultural production. Elevated atmospheric CO_2 almost always increases plant production. Higher temperatures can potentially increase or decrease grain yields [17]. Climate change also has an impact on the accumulation of minerals and protein in crop plants, with eCO_2 being the underlying factor of most of the reported changes. The effects are clearly dependent on the type, intensity and duration of the imposed stress, plant genotype and developmental stage. Strong interactions (both positive and negative) can be found between individual climatic factors and soil availability of nitrogen (N), potassium (K), iron (Fe) and phosphorous (P). The development of future interventions to ensure that the world's population has access to plentiful, safe and nutritious food may need to rely on breeding for nutrients under the context of climate change, including legumes in cropping systems, better farm management practices and utilization of microbial inoculants that enhance nutrient availability. Therefore, the objective of this paper is to review the impacts of climate change on crop physiology and food quality.

2. Crop Response to Climate Change

Several features of climate change such as higher atmospheric CO_2 concentration, increasing temperature and changed rainfall (reduced or increased) all have different impacts on plant production and crop yield. In combination, these effects can either increase or reduce plant production, and the net effect of climate change on crop yield depends on the interactions between these factors. Crops sense and respond directly to rising CO_2 through photosynthesis and stomatal conductance, and this is the basis for the CO_2 fertilization effect on crop yield. These responses are highly dependent on temperature. Therefore, understanding how crop species will respond to these environmental changes is crucial for maximizing the potential benefits of elevated CO_2, for which agronomic practice needs to adapt as both temperature and CO_2 rise [4].

2.1. Elevated Atmospheric CO_2 Concentrations

Elevated CO_2 has two main effects on crop growth. First it increases the intercellular CO_2 concentration, leading to increased net photosynthesis rates, and at the same time reduces stomatal conductance, resulting in reduced transpiration. Many experiments have shown that higher CO_2 increases plant biomass production and yield. C3 species (e.g. wheat, soybean, potatoes and sunflower) and C_4 species (e.g. maize, sorghum, and millet) have a different degree in response to elevated CO_2. On average, doubling CO_2 concentrations increases photosynthesis by 30 –50% in C_3 species and by 10-25% in C_4 species. Increases in crop yield are lower than the photosynthetic response; however, at 500 –550 ppm, grain yields of C_3 crops still increase by 10 -20% while C_4 crop yields are up to 13% higher [27].

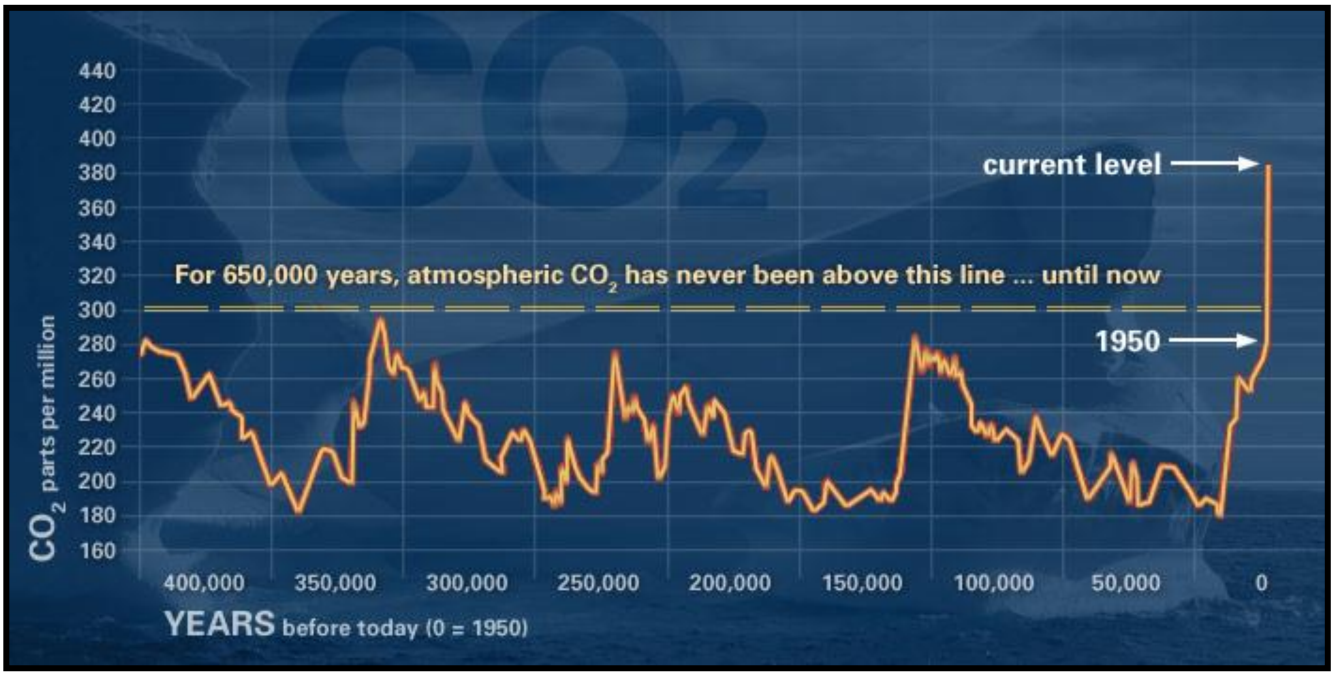

Figure 1. *Increasing and prediction of the concentration of carbon dioxide in the atmosphere.*

The impact of elevated CO_2 on plant production depends on water and nutrient availability. The highest response to elevated CO_2 is found under water-limiting conditions [14] because higher CO_2 concentrations increase leaf and plant water use efficiency. Low nutrient availability can reduce the yield benefit of elevated CO_2. The impact of elevated CO_2 at field and farm levels is probably lower than those estimated in well-controlled experimental conditions, due to production-limiting factors such as low nutrient availability, pests and weeds [27]. An important indirect effect of higher atmospheric CO_2 is reduced plant nutrient concentrations, which can result in lower grain quality. An indirect effect of elevated atmospheric CO_2 increase will be an increase in canopy temperatures via the reduction in stomatal conductance. There is evidence in both wheat and cotton that selection for improved grain yields in breeding programs has been associated with selection for high stomatal conductance, resulting in 'heat avoidance through evaporative cooling in hot environments [20]. Reduced stomatal conductance due to atmospheric CO_2 increase might therefore have additional effects on crop growth and development similar to an increase in temperatures.

2.2. Temperature

Temperature has an impact on most plant and crop-level processes underlying yield determination and hence the complexity of the final yield response. Where certain crops are grown near their limits of maximum temperature tolerance, heat spells can be particularly detrimental. Conversely, in cooler regions, increased annual mean temperatures since the 1980s have contributed to the reported increase in agriculture production higher temperatures can negatively impact plant production indirectly through accelerated phenology with less time for accumulating biomass [16]. As a result of climate change, not only average temperature will increase but extreme temperatures will also occur more often than expected, based on the average increase.

These extreme temperature events can have large negative impacts on plant growth and yield. In wheat, temperature increases around anthesis can reduce potential grain weight and yield. In cool climates and at higher altitudes, higher temperatures can increase the length of the potential growing season. The impact of increasing temperatures can vary widely between crop species. The optimum temperature for leaf photosynthesis and plant growth is higher for C_4 plants than for C_3 plants. Species with a high base temperature for crop emergence, such as maize, sorghum, millet, sunflower and some of the legumes such as mung bean and cowpea could benefit from increasing temperatures in cool regions. Most of the small-grain cereals, legumes such as field pea and lentil, linseed and oilseed *Brassica* spp. with a low base temperature [30] could result in an advanced phenology with increased temperatures.

An indirect effect of global warming can be a higher plant water demand due to increased transpiration at higher temperatures, which can potentially reduce plant production. In dry-land agriculture, this can directly limit plant growth, while in irrigated systems; increased temperatures could result in higher irrigation water demands in combination with increased losses through evaporation. However, if future temperature changes are similar to the changes in the last 50 years, during which global minimum temperatures have generally increased twice as fast as maximum temperatures, resulting in a reduced diurnal temperature range. In addition, higher atmospheric CO_2 concentrations can partly compensate for the increased water demands due to higher temperatures, through a lower stomatal conductance that reduces transpiration. Reduced leaf transpiration as a consequence of higher CO_2 will also increase leaf temperature, with an increased chance of plant damage due to heat stress. Plants grown at higher atmospheric CO_2 tend to have a higher leaf water potential which results in reduced drought stress [29].

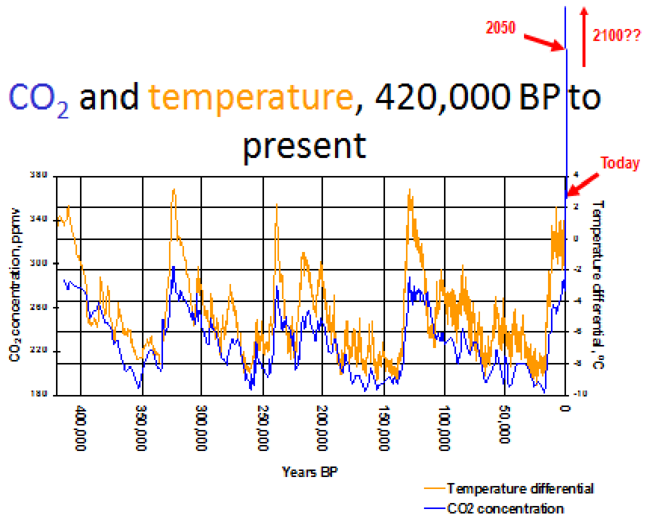

Figure 2. *The concentration of Carbon dioxide and temperature in the atmosphere from 420 BC to present.*

2.3. Rainfall and Rainfall Variability

Global warming is likely to change precipitation amounts and patterns differently across the globe. Total annual rainfall tends to increase at higher latitudes and near the equator, while rainfall in the sub-tropics is likely to decline and become more variable. Changing rainfall amounts can have both negative and positive impacts on agricultural production. For example, in semi-arid environments, higher rainfall could increase growth, whereas less rainfall could further limit plant production. In contrast, in high-rainfall zones, too much rainfall can result in soil waterlogging, which damages crop growth or results in nutrient leaching in sandy soils, and reduced rainfall on these soils could limit the negative impacts of waterlogging and nutrient leaching [12].

Not only the total rainfall amount but also the rainfall distribution plays an important role for determining crop yields. Rainfall around anthesis ensuring water supply during the grain set and grain-filling periods is particularly critical for yield in annual crops [5]. Changing future in-season rainfall distribution will therefore have an impact on crop growth and yield. Balancing growth and water use before and after anthesis is one of the tools to manage uneven rainfall distribution and scarce irrigation water. Management options to change the seasonal water use of crops include sowing time, nutrient management, plant density and cultivar choice [5].

Another specific aspect of future rainfall change is increased rainfall variability through an increase in extreme events. Extreme events could include a higher drought frequency with long-term effects on farm variability that could reduce crop production and yields below what is expected, based on the average climate change [11]. Particularly critical are changes in rainfall intensity and the distribution of small versus large rainfall events, which can have significant consequences for crop production via the impact on soil infiltration depth, run-off, deep drainage, soil mineralization and crop Water use efficiency [23].

2.4. Solar Radiation

Reduction in solar radiation can potentially have a considerable negative impact on agricultural production which can be partially or completely compensated by the associated increase in the diffused light fraction. Plant production is primarily driven by sunlight, as plant cells transform solar energy into sugars. Hence, a reduction in solar radiation can potentially reduce photosynthesis and growth. However, photosynthesis is often limited by nutrient and/or water availability. Lower solar radiation also reduces potential evaporation [21]. In water-limited environments, this can increase plant-available water and thus increase plant production. Reduced evapotranspiration can also increase drainage and nutrient leaching, which can have large negative ecosystem impacts. A reduction in solar radiation is usually accompanied by an increase in the diffused light fraction. An expected decrease in photosynthesis with less radiation assumes light-saturated photosynthesis is critical for photosynthesis, but this could be overridden by the canopy light distribution that could be favoured by dimming [22].

2.5. Ozone

Ozone (O_3) is a form of oxygen that is an atmospheric pollutant at ground level. Most of the O_3 in the atmosphere (about 90%) is in the stratosphere, the remaining being in the troposphere. The ozone in the troposphere and the stratosphere has different effects on life on the earth, depending on its location. Stratospheric ozone plays a beneficial role by absorbing solar ultraviolet radiation (UV) from reaching the earth's surface.

Increased levels of UV have been measured with a general erosion of the stratospheric ozone layer in the past decades (World Meteorological Organization [33]. These increased levels of UV have shown to reduce leaf expansion and biomass accumulation in plants and could impact on plant–herbivore interactions by increasing plant resistance to insects. Ozone is a strong oxidiser; therefore ozone closer to the earth's surface is potentially destructive to plants. In crops, ozone can create reactive molecules that destroy rubisco, an enzyme crucial for photosynthesis, and makes crop leaves age faster. In general, elevated CO_2 can stimulate crop growth, but increasing O_3 levels at ambient CO_2 results in a decline in crop yield in many species. This negative effect results from a limitation of photosynthetic C assimilation due to a reduction in the activity and amount of rubisco associated with accelerated leaf senescence [7]. Moreover, ozone impairs source-to-sink translocation of photosynthesis. In addition to its effect on crop yield, O_3 affects yield quality. For example, report showed that grain N concentration generally increased with increasing O_3, leading to a better baking quality of the flour in spring wheat. However, increasing O_3 had a negative impact on the tuber quality of potato [28]. In general, elevated O_3 has negative effects on crop growth and influences the magnitude of the yield enhancement by elevated CO_2.

3. Nitrogen and Other Essential Nutrients

Nitrogen availability to plants, more than any other environmental factor, determines their responses to elevated CO_2. This has been associated with the fact that elevated CO_2 results in decreased N content (typically by 13– 16%) in plant tissues regardless of the CO_2-enrichment technology. It is likely that decreases in tissue N result to some extent from (i) the accumulation of carbohydrates and other organic compounds as a consequence of CO_2 stimulation of photosynthesis, (ii) reduced uptake of N from the soil under high CO_2 due to lower transpiration rates resulting from decreased stomatal conductance, and (iii) impaired nitrate assimilation associated with decreases in the photorespiration pathway at elevated CO_2, as found in C_3 species such as wheat and tomato [3]. In any case, it should be noted that decreases in the concentrations of Rubisco and other photosynthetic enzymes are found at elevated CO_2 without negatively compromising carbon acquisition. Therefore, decreased leaf protein may lead to reduced sink (e.g., grains and tubers) protein concentration as the N supply to sinks during filling is largely from translocation from catabolized proteins in senescing photosynthetic tissues. [10]. Accordingly, CO_2 effects on primary carbon fixation may also alter the concentrations of different elements that respond similarly to N, such as Ca, S, Mg, Zn and K. Furthermore, mass flow, which is generally more important for uptake of mobile elements such as N, and diffusion, which is more important for immobile elements such as P, are both predicted to be changed under elevated CO_2 due to alterations in transpiration and soil moisture [13].

4. Consequences of Climatic Changes for Phenology and Crop Yield

Temperature and interactions

With regard to warmer temperatures, crop yield can be affected at any time from sowing to grain maturity, but it is the time around flowering, when the number of grains per land area is established, and during the grain-filling stage, when the average grain weight is determined, that high temperatures have the most impact on the final harvestable crop, as found in cereals. Thus, understanding how environmental factors signal phenological processes such as flowering will be extremely relevant for future food production, since a large part of food comes as grains/seeds. In this context, any change in flowering time could affect not only seed production but also food composition [25].

Moreover, at elevated CO_2, tissue temperatures are often increased due to lower evaporative cooling. In fact, results from on rice show that elevated CO_2 (+300 ppm over ambient concentration) may even increase sterility and thus depress crop yield at high temperatures, possibly by further increasing temperature within the plant canopy. However, seed yield response to CO_2 may depend on the sensitivity of individual cultivars to temperature, especially during the reproductive development stage, as demonstrated in peanut by [2]. In fact, modeling studies suggest that climate change without CO_2 fertilization could reduce rice, maize and wheat yields by up to 37% in the next 20–80 years. At warmer temperatures, the yield of wheat may decline up to 10% per 1℃ rise in mean seasonal temperature. Hot temperatures (32–36℃) can also greatly reduce seed set in many annual crops if elevated temperatures coincide with a brief critical period of only 1-3 days around the time of flowering. In groundnut, for example, [2] noted that, from between 32 and 36℃ and up to 42℃, the percentage fruit set fell from 50% of flowers to zero and the decline in rate was linear, illustrating the sharpness of response of crop plants to temperatures between 30 and 35℃ during the flowering and fruiting periods.

5. Consequences on Food Quality

A major omission of the effects of a globally altered environment on crops is concerned with food quality. Apart from an overall decrease in N and protein concentrations, as shown under elevated CO_2, the nutritional value and the quality of the edible products of most food and forage crops are largely unknown. Moreover, the available information is somewhat contradictory, rendering insufficient knowledge to draw firm conclusions on how the current and ongoing climatic changes will affect food quality for either human or animal nutrition.

5.1. Carbohydrates

The effects of temperature and elevated CO_2 on carbohydrate composition of food crops are mixed and probably reflect differences in experimental conditions (e.g., CO_2 enrichment technologies and rooting volume) in addition to being species- or even cultivar-dependent. However, the preponderance of evidence suggests that increases in temperature should have a larger effect than elevated CO_2 on carbohydrate composition. In soybean seeds, carbohydrate composition significantly changed with increasing temperature from 18/13℃ to 33/28℃ (day/ night). Whereas sucrose concentration increased, stachyose decreased slightly; other sugars, such as glucose, raffinose and fructose did not change significantly with rising temperature [32]. Studies has indicated, the combined effects of temperature and CO2 on the composition of soybean seeds, found that total soluble sugars and starch decreased as temperature increased from 28/18℃ to 44/34℃ (day/night), while the proportion of soluble sugars to starch decreased, with the effects of elevated CO2 (700 ppm) being comparatively negligible [26]. In wheat, small increases in temperature (2–4℃) may also have more than twice the effect of CO2 on grain quality, as shown by [31]. who noted that starch content, starch grain size and number, and gelatinization were all altered in complex ways with temperature, but with little effect of increased CO2.

High temperature (37/17℃) from flowering to grain maturity caused a significant reduction in the starch accumulation period in developing wheat grains compared with plants grown under control (24/17℃; day/night) conditions. In any case, [19] noted only minor alterations in carbohydrate composition in wheat grains in response to CO2 enrichment e.g., slight increases in hemicellulose concentration but unaltered concentrations of water soluble carbohydrates, cellulose and lignin.

5.2. Minerals

Studies showed that two wheat and two barley cultivars grown in pots under ambient and two elevated CO_2 in OTCs. They found overall decreases for most macronutrients and micronutrients under high CO_2, with nutrient concentrations more affected in straw than in grains, although the responses to elevated CO_2 were species- and cultivar-dependent. Performed a meta-analysis based on 25 studies covering 19 herbaceous and 11 woody species and concluded that leaf concentrations of macronutrients and micronutrients such as Fe, Zn, Mn and Cu all decreased under elevated CO2 as compared to controls grown at ambient CO2. For the two major staple crops, rice and wheat, most studies suggest that, overall, decreased concentrations of nutrients, with the exception of a few minerals, will be the norm in a high-CO_2 world. In rice, [24] found lower concentrations of four out of five measured elements: N (14%), P (5%), Fe (17%) and Zn (28%), but Ca increased (32%) under elevated CO2. In wheat, [13] analyzed five published studies and noted slight decreases (ranging from 3% to 10%, though significant) in P, Mg and Zn, and decreases superior to 10% in the concentrations of N, Ca, S, Fe, and Zn, whereas K concentration increased slightly.

5.3. Lipids

In soybean, oil content was positively correlated with increasing temperature from 25℃ to 36℃. Studied showed that the combined effects of temperature and CO2 on the composition of soybean seeds and found that oil yield was highest at 32/22℃ (day/night) and decreased with further increase in temperature. Oleic acid concentration increased with increasing temperature, whereas linolenic acid decreased. Similar results were also obtained in sunflower [18].

5.4. Proteins and Their Fractions

Elevated atmospheric CO_2 (540–958 ppm) can affect the food quality of major food crops as the study indicated that in a meta-analysis to examine the effect on the protein concentration. For wheat, barley and rice, the reduction in grain protein ranged from 10% to 15% of the value of ambient CO_2 (315-400 ppm). For potato, the high- CO_2 induced reduction in tuber protein concentration was 14% and, for soybean, there was a much smaller, although statistically significant, decrease in protein concentration of 1.4%. In wheat, the proportions and properties of the two main classes of gluten storage proteins (glutenin and gliadin), each of which comprises between 35% and 45% of the total grain proteins, are primarily responsible for dough and bread-making quality [9]. Although data on the effects of high CO_2 on protein quality are currently limited, changes in dough properties and bread-making rheological properties in wheat are to be expected at elevated CO_2. [9] Concluded that, in addition to the reduced protein concentration and possible changes in protein composition in grains, the concentrations of amino acids were significantly reduced by between 7.7% and 23.9% due to CO^2 enrichment except for proline, glycine, tyrosine, histidine, and lysine.

6. Conclusions

Impact of climate change has both a positive and negative responses of crop production components such as photosynthesis, respiration, water relation, enzymatic activities, biomass accumulation etc. Elevated CO_2 has two main effects on crop growth. It increases the intercellular CO_2 concentration, leading to increased net photosynthesis rates, and at the same time reduces stomatal conductance, resulting in reduced transpiration. This leads to make variation in the yields of crops in C_3 and C_4 species. On average, doubling CO_2 concentrations increases photosynthesis by 30-50% in C_3 species and by 10-25% in C_4 species. Increases in crop yield are lower than the photosynthetic response; however, at 500 –550 ppm, grain yields of C_3 crops still increase by 10-20% while C_4 crop yields are up to 13% higher, while in increasing temperature also has its own impact on particularly in crop production and in general in the ecosystem.

The increment in temperature may impose on crop nutrient absorption due to reduce respiration and stomatal closure this leads to poor content in food quality for instance it affects protein content, lipids, carbohydrate etc. In order to alleviate climate variability in plant physiology/crop production different adaptation and mitigation measures should be taken like Biological and physical soil conservation methods (terracing, afforestation, reduce land degradation), precise use of Agrochemicals (inorganic fertilizer and pesticides), drip and sprinkler irrigation for wise use of water, water harvesting, improved varieties tolerant to abiotic and biotic stress.

Abbreviations

CO_2	Carbon Dioxide
GHG	Green House Gases
PPM	Parts Per Million
WMO	World Metrology Organization

Author Contributions

Jemal Bekere Adem is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Anderson JT, Inouye DW, McKinney AM, Colautti RI, Mitchell-Olds T (2012) Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change. Proc Biol Sci 279: 3843–3852.

[2] Bannayan, M., Tojo Soler, C. M., Garcia y Garcia, A., Guerra, L. C., & Hoogenboom, G. (2009). Interactive effects of elevated [CO_2] and temperature on growth and development of a short- and long-season peanut cultivar. Climatic Change, 93, 389–406.

[3] Bloom, A. J. (2006). Rising carbon dioxide concentrations and the future of crop production. Journal of the Science of Food and Agriculture, 86, 1289–1291.

[4] Challinor, A. J. and Wheeler, T. R (2008b). Crop yield reduction in the tropics under climate change: Processes and uncertainties. Agricultural and Forest Meteorology, 148, 343–356.

[5] Fischer, R. A., (1979). Growth and water limitation to dryland wheat yield in Australia: A physiological framework. J. Aust. Inst. Agric. Sci. 45, 83–94.

[6] Franks SJ, Sim S, Weis AE (2007). Rapid evolution of flowering time by an annual plant in response to a climate fluctuation. Proc Natl Acad Sci USA 104: 1278–1282.

[7] Grandjean, A., Fuhrer, J.,(1989). Growth and leaf senescence in spring wheat (*Triticum aestivum*) grown at different ozone concentrations in open-top fi eld chambers. Physiol. Plant. 77, 389 – 394.

[8] Hay, R., & Porter, J. (2006). The physiologies of crop yield (2nd ed.). Oxford: Blackwell.

[9] H ögy, P., & Fangmeier, A. (2008). Effects of elevated atmospheric CO_2 on grain quality of wheat. Journal of Cereal Science, 48, 580–591.

[10] IPCC (2013) Climate Change: The Physical Science Basis. Intergovernmental Panel on Climate Change, Cambridge, UK.

[11] IPCC, (2007). Climate Change. Cambridge University Press, New York.

[12] Jiang, D., Fan, X., Dai T., Cao, W. (2008). Nitrogen fertilizer rate and post-anthesis waterlogging effects on carbohydrate and nitrogen dynamics in wheat.. Plant Soil 304, 301 – 314.

[13] Loladze, I. (2002). Rising atmospheric CO_2 and human nutrition: Toward globally imbalanced plant stoichiometry? Trends in Ecology & Evolution, 17, 457–461.

[14] Manderscheid R., Weigel, H. J. (2007). Drought stress effects on wheat are mitigated by atmospheric CO 2 enrichment. Agron. Sustain. Dev. 27, 79-87.

[15] Medvigy D, Beaulieu C (2012) Trends in daily solar radiation and precipitation coefficients of variation since 1984. J Clim 25: 1330–1339.

[16] Menzel, A., Sparks, T. H, Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kubler, K., Bissolli, P., Braslavska, O. G., Briede, A., Chmielewski, F. M., Crepinsek, Z., Curnel, Y., Dahl, A., Defi la, C., Donnelly, A., Filella, Y., Jatczak, K., Mage, F., Mestre, A., Nordli, O., Penuelas, J., Pirinen, P., Remisova, V., Scheifi nger, H., Striz, M., Susnik, A., Van Vliet, A. J. H., Wielgolaski, F-E., Zach, S., Zust, A. N. A. (2006). European phenological response to climate change matches the warming pattern. Glob. Chang. Biol. 12, 1969 –1976.

[17] Peng, S., Laza, R. C. Visperas, R. M., Khush, G. S., Virk, P., Zhu, D., (2004b). Rice: Progress in breaking yield ceiling. In: Proceeding of the 4th International Crop Science Congress, Brisbane, Australia.

[18] Polley, H. W. (2002). Implications of atmospheric and climate change for crop yield. Crop Science, 42, 131–140.

[19] Porteaus, F., Hill, J., Ball, A. S., Pinter, P. J., Kimball, A., Wall, G. W., et al. (2009). Effect of free air carbon dioxide enrichment (FACE) on the chemical composition and nutritive value of wheat grain and straw. Animal Feed Science and Technology, 149, 322–332.

[20] Radin J. W., Lu, Z. M., Percy, R. G., Zeiger, E. (1994). Genetic-variability for stomatal conductance in pima cotton and its relation to improvements of heat adaptation. Proc. Natl. Acad. Sci. U.S.A. 91, 7217-7221.

[21] Roderick, M. L., Farquhar, G. D. (2002). The cause of decreased pan evaporation over the past 50 years. Science 299, 1997-1998.

[22] Rodriguez, D., Sadras, V. O. (2007). The limit to water use efficiency in eastern Australia. I. Gradients in the radiation environment an atmospheric demand. Aust. J. Agric. Res. 58, 287 – 302.

[23] Sadras V. O., Rodriguez, D. (2007). The limit to wheat water-use efficiency in eastern Australia. II. Influence of rainfall patterns Aust. J. Agric. Res. 58, 657 – 669.

[24] Seneweera, S. P., & Conroy, J. P. (1997). Growth, grain yield and quality of rice (Oryza sativa L.) in response to elevated CO_2 and phosphorus nutrition. Soil Science and Plant Nutrition, 43, 1131–1136.

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

[26] Thomas, J. M. G., Boote, K. J., Allen, L. H., Gallo-Meagher, M., & Davis, J. M. (2003). Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance. Crop Science, 43, 1548–1557.

[27] Tubiello, F. N., Soussana, J. F., Howden, S. M. (2007). Climate change and food security special feature: Crop and pasture response to climate change. Proc. Natl. Acad. Sci. U.S.A. 104, 19686 – 19690.

[28] Vorne, V., Ojanper ä, K., De Temmerman, L., Bindi, M., H ögy, P., Jones, M., Lawson, T., Persson, K. (2002). Effects of elevated carbon dioxide and ozone on potato tuber quality in the European multiple-site experiment CHIP-project. Eur. J. Agron. 17, 369 – 381.

[29] Wall, G. W. (2001). Elevated atmospheric CO 2 alleviates drought stress in wheat. Agric. Ecosyst. Environ. 87, 261 – 271.

[30] Ward JK, Kelly J (2004). Scaling up evolutionary responses to elevated CO_2: lessons from Arabidopsis. Ecol Lett 7: 427–440.

[31] Williams, M., Shewry, P. R., Lawlor, D. W., & Harwood, J. L. (1995). The effects of elevated temperature and atmospheric carbon dioxide concentration on the quality of grain lipids in wheat (Triticum aestivum L.) grown at two levels of nitrogen application. Plant, Cell and Environment, 18, 999–1009.

[32] Wolf, R. B., Cavins, J. F., Kleiman, R., & Black, L. T. (1982). Effect of temperature on soybean seed constituents: Oil, protein, moisture, fatty acids, amino acids and sugars. Journal of the American Oil Chemists' Society, 59, 230–232.

[33] World Meteorological Organization (WMO), 1995. Scientific assessment of ozone depletion. World Meteorological Organization Report no. 37, Geneva.