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Crop Growth and Yield under Changing Climate: A Review

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Abstract: Climate change will affect agriculture through higher temperatures, greater crop water demand, more variable rainfall and extreme climate events such as heatwaves, floods and droughts. Marginal areas, where low yields and poverty go hand in hand, may become even less-suited for agriculture as a result of land degradation through deforestation, wind and water erosion and repetitive tillage. Many impact studies point to severe crop yield reductions in the next decades without strong adaptation and mitigation measures particularly in Sub-Saharan Africa and South Asia, where rural households are highly dependent on agriculture and farming systems are highly sensitive to temperature increases and volatile climate. Assessment based on a pessimistic assumption about global warming estimates that by the 2080s world agricultural productivity will decline by 3-16%. The loss in Africa could be 17-28%. Agriculture is therefore the sector most vulnerable to climate change, directly impacting the economic activity of countries and increasing the risk of hunger and malnutrition. This leads to a vicious cycle, as the poorest suffer the worst consequences of the adverse weather caused by climate change, whilst having the least capacity to deal with them, due to poor nutrition, the number of people affected, drinking water shortages and poor sanitation; this, in turn, leads to the rapid spread of infectious diseases and failings in social protection systems. While agriculture is the sector most vulnerable to climate change, it is also a major cause, directly accounting for about 14% of greenhouse gas emissions, or approximately 30% when considering land-use change, including deforestation driven by agricultural expansion for food, fiber and fuel. And yet, agriculture can be a part of the solution: helping people to feed themselves and adapt to changing conditions while mitigating climate change. Despite the climate change-related decline in food-crop yields mentioned above, there is great potential to counter this by adopting climate-smart agriculture.

Key words: Adaptation · Climate Change · Climate Impact · Crop Growth · Crop Yield · Mitigation

INTRODUCTION

There is wide scientific consensus that global climate is changing in part as a result of human activities [1, 2] and that the social and economic costs of slowing it down and responding to its impacts will be large [3]. Current data demonstrate that the climate is changing globally at an unprecedented rate and that unparalleled levels of human-induced greenhouse gas emissions, especially carbon dioxide, are causing an increase in global temperatures that creates changes in the earth's weather. Atmospheric concentrations of carbon dioxide have increased from a pre-industrial value of 278 parts per million (ppm) to 379 ppm in 2005. It is now generally accepted that this climate change is the result of increasing concentrations of carbon dioxide, methane, nitrous oxide and other greenhouse gases in the atmosphere [1]. Recent scientific research has concluded that the increased atmospheric concentration of greenhouse gases will have significant impacts on the Earth's climate in the coming decades. Assuming no emission control policies, the Intergovernmental Panel of Climate Change (IPCC) predicted that average global surface temperatures will increase by 2.8°C on average

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during this century, with best-guess increases ranging from 1.8 and 4.0°C [4]. Global warming would alter the natural climate and environmental systems in many ways, leading to an increased frequency of extreme weather events, rising sea levels, a reversal of ocean currents and changes in precipitation patterns. Several factors that directly connect climate change and agricultural productivity include, average temperature increase; change in rainfall amount and patterns; rising atmospheric concentrations of CO_2, pollution levels such as tropospheric ozone and climate variability/change with the associated extreme events such as drought and flooding [5-8]. These changes could impact social-economic activities, with serious implications for the wellbeing of humans long into the future.

Agriculture is one of the most vulnerable sectors to the anticipated climate change [9]. It is increasingly and often negatively affected by rising temperatures and climatic instability, but it is itself also a major contributor, accounting for up to 30 percent of global greenhouse gas emissions [10]. Despite the technological advances in the second half of the 20th century, including the Green Revolution, weather and climate are still key factors in determining agricultural productivity in most areas of the world. The predicted changes in temperatures and rainfall patterns, as well as their associated impacts on water availability, pests, disease and extreme weather events, are all likely to affect substantially the potential of agricultural production. Changing weather patterns or extreme weather events, such as floods or droughts, can have negative consequences for agricultural production [11, 12]. Climate change could have both positive and negative impacts and these could be measured in terms of effects on crop growth, availability of soil water, soil fertility and erosion, incidents of pests and diseases and sea-level rise [5-8]. It is generally agreed that agricultural impacts will be more adverse in tropical areas than in temperate areas. Developed countries will largely be beneficiaries of cereal productivity. By contrast, many of today's poorest developing countries are likely to be negatively affected [1]. In these countries, the next 50 to 100 years will see widespread declines in the extent and potential productivity of cropland [13] particularly in sub-Saharan Africa and southern Europe [14]. Therefore, this paper reviews the major determinants of crop growth and yield under changing climate.

Climate Change and its Consequence: Weather is the set of meteorological conditions such as wind, rain, snow, sunshine, temperature, etc. at a particular time and place. By contrast, the term climate describes the overall long-term characteristics of the weather experienced at a place [15]. The ecosystems, agriculture, livelihoods and settlements of a region are very dependent on its climate. The climate, therefore, can be thought of as a long-term summary of weather conditions, taking account of the average conditions as well as the variability of these conditions. The fluctuations that occur from year to year and the statistics of extreme conditions such as severe storms or unusually hot seasons are part of the climatic variability. Climate has changed many times in response to a variety of natural causes but the term 'climate change' usually refers to those changes that have been observed since the early 1900s and include anthropogenic and natural drivers of climate [1]. The main human influence on global climate is through emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4) (Figure 1). At present, about 6.5 billion tonnes of CO_2 are emitted globally each year, mostly through burning fossil fuels. Changes in land use mean a further net annual emission of 1-2 billion tonnes of CO_2 [2]. Such increasing concentrations of greenhouse gases in the atmosphere since the industrial revolution have trapped more energy in the lower atmosphere, altering global climate. Certain activities create GHGs, which capture heat and energy in the atmosphere and alter long-term climate cycles. This phenomenon is called the greenhouse effect [2]. The Earth's greenhouse effect is, in fact, a natural phenomenon that helps regulate the temperature of the planet. When the sun heats the Earth, some of this heat escapes back into space. The rest of the heat, also known as infrared radiation, is trapped in the atmosphere by clouds and GHGs, such as water vapor and CO_2. If all of these GHGs did not exist, the planet would be approximately 60 degrees colder than it is today. The levels of these gases are increasing at a rate faster than at any time during the past 100, 000 years and are causing subsequent increases in global temperatures. The cumulative effects of increased GHG emissions and their role in the atmosphere and weather patterns are known as climate change.

The different GHGs have different potencies in the atmosphere. The potency of a GHG is referred to as its global warming potential and is commonly expressed as a carbon dioxide equivalent or CO_2e. Two common GHGs-methane and nitrous oxide are 21 and 310 times more potent than CO_2, respectively; that is, their presence in the atmosphere traps considerably more heat than CO_2. Potential consequences of a changing climate include decreasing crop yields because of the rise in temperature

Fig. 1: Greenhouse gas emissions by different sectors and agricultural sector. Source: [2]

and changes in precipitation and the displacement of traditional crops, forcing producers to change the crops they can grow to adapt to the new climate [16, 17]. Increasing temperatures will also intensify the water cycle. Increasing evapotranspiration will make more water available in the atmosphere for storms but will contribute to drying over some other areas. As a result, storm-affected areas are likely to experience increases in precipitation and increased intensity, which can cause flooding, the loss of valuable top soil and crop damage [18]. In a warming climate, extreme events like floods and droughts are likely to become more frequent. More frequent floods and droughts will affect water quality and availability [19]. For example, increases in drought in some areas may increase the frequency of water shortages and lead to more restrictions on water usage, such as for crop irrigation. An overall increase in precipitation may increase water availability in some regions but also create greater flood potential and waterlogged soils, which can reduce crop production. Rising temperatures will also warm surface waters, causing them to be more susceptible to algae growth and making the control of non point source pollution more critical.

Higher temperatures will cause more evapotranspiration, drying soils more rapidly and raising the humidity of the atmosphere, which can decrease crop water uptake. The implications of decreased crop water uptake and variable soil moisture level are not generally well-understood, but crops rely on water uptake to supply essential nutrients, so anything that decreases water uptake will need to be considered for its consequences on crop productivity. Increased temperatures will reduce organic carbon levels in the soil via oxidation, which can further reduce soil moisture levels and subsequently affect crop productivity [19]. Increased temperatures may impact the germination and senescence of some crops. Warmer temperatures may make many crops grow more quickly but could also consequently reduce the yields of some crops. Crops tend to grow faster in warmer conditions, but for some crops, such as grains, rapid growth reduces seed maturity and nutrition and can ultimately reduce yields. Greater CO_2 concentrations increase plant respiration rates. As part of the carbon cycle, plants use energy from the sun to photosynthesize carbohydrates from CO_2 and greater CO_2 concentrations can result in greater carbohydrate production [20]. A small amount of warming coupled with increasing CO_2 could benefit certain crops, although the impact on crops depends also on the availability of water and nutrients.

Climate change effects on agriculture also include the effects of changing climate conditions on resources of key importance to agricultural production, such as soil and water [21]. Seasonal precipitation affects the potential amount of water available for crop production, but the actual amount of water available to plants also depends upon soil type, soil water holding capacity and infiltration rate. Healthy soils have characteristics that include appropriate levels of nutrients necessary for the production of healthy plants, moderately high levels of organic matter, a soil structure with the good aggregation of the primary soil particles and macro-porosity, moderate pH levels, thickness sufficient to store adequate water for plants, a healthy microbial community and absence of elements or compounds in concentrations toxic for the plant and microbial life. Several processes act to degrade soils including, erosion, compaction, acidification, salinization, toxification and a net loss of organic matter. Several of these processes are sensitive to changing climate conditions. Changes to the rate of soil organic matter accumulation will be affected by climate through soil temperature, soil water availability and the amount of organic matter input from plants. Changing climate will contribute to the erosivity from rainfall, snow melt and wind [20]. Rainfall's erosive power will increase if increases in rainfall amount are accompanied by increases of intensity. Changes in production practices can also have effects on soil erosion that may be greater than other effects of climate change. Tillage intensity, crop selection, as well as planting and harvest dates can significantly affect runoff and soil loss. Soil conservation practices will therefore be an important element of agricultural adaptation to climate change.

Factors Affecting Crop Growth and Yield

Temperature: Temperature alterations can take many forms: changes in average temperature; changes in day time high and night time low temperatures; and changes in the timing, intensity and duration of extremely hot or cold weather [22]. Global food production is projected to increase overall with increases in average temperatures of 1-3°C, but if temperature rises are above 3°C then global food production will decrease [15]. Temperature is fundamental in determining crop quality, quantity and where it can be grown. Due to the nature of this fundamental relationship in biology and ecology, any changes in temperature through climate change will have large impacts on crop production. Average air temperatures are expected to increase during the next 30 years [16]. Such temperature increase will almost inevitably affect agricultural products, as all plants have minimum, maximum and optimum temperatures that define their response to temperature. The minimum and maximum temperatures are the boundaries for growth; between these extremes is an optimum temperature that allows the greatest growth. Beyond a certain point, higher air temperatures adversely affect plant growth, pollination and reproductive processes [19, 23]. However, as air temperatures rise beyond the optimum, instead of falling at a rate equal to the temperature increase, crop yield losses accelerate. For example, analysis indicates that yield growth for corn, soybean and cotton gradually increases with temperatures up to 29°C to 32°C and then decreases sharply as temperature increases beyond this point [24]. Depending upon the current temperatures and thresholds, the increased temperature can sometimes result in a yield increase. Easterling *et al*. [15] have shown that an increase in temperature of up to 3°C could result in increased yields of cereals in temperate environments, whereas in tropical countries yields could start decreasing with a small increase in temperature. This has implications for the global food trade. It is expected that due to rising food demands and decreased productivity associated with global warming in tropical countries, trade flows of food would increase from temperate countries to the tropics. Fischer *et al*. [25] estimate that by 2080 cereal imports by developing countries would rise by 10-40%.

An increase in temperature, depending upon the current ambient temperature, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distribution of pest populations thus developing a new equilibrium between crops and pests, hasten nutrient mineralization in soils, decrease fertilizer use efficiencies and increase evapotranspiration. The stages of growth at which weather extremes occur are important in determining yield losses. For example, a temperature increase for a short period around pollen formation, dispersal and germination can lead to partial/complete sterility in crops [26]. Variations in the length of the thermal growing season will generally affect temperate perennial species (apples, cherry and grapes). Most temperate perennials require an adequate period of chilling hours during dormancy before they can resume active growth. Inadequate chilling impairs the development and/or expansion of vegetative and reproductive organs, which will affect fruiting. Higher temperatures can also affect the marketability of fruits and vegetables. The increased rates of respiration caused by higher temperatures lead to greater use of sugars by the plants. As a result, less sugar remains in the harvested product and this can reduce its market value [20]. These effects become more serious as temperatures continue to rise during the grain-filling or fruit maturation stage [27]. All stages of crop development are sensitive to temperature. Development generally accelerates linearly within certain temperature boundaries, but with extreme temperatures, the relationship becomes non-linear and increasingly difficult to predict. Higher temperatures often lead to heat stress which can result in increasing sterility and lower overall productivity in crops. As temperature rises there is increased evaporation from plants and soils resulting in increased water requirements while lowering water availability, which causes further stress to the crop. The length of crop growth cycles is temperature-dependent. Increased temperature leads to the time between sowing and harvesting being shorter. This could be beneficial in terms of a greater number of cropping cycles, thus increasing yield over a year. However, such a reduction in the duration of the crop cycle could lead to earlier senescence thus harming productivity. Additionally, a greater number of cropping cycles will lead to greater inputs, resulting in soil nutrient and moisture depletion, greater exposure to pests and greater pressure on what might already be marginal land.

Most crops can tolerate higher day time temperatures during vegetative growth, with photosynthesis reaching an optimum at between 20°C and 30°C [28]. During the reproductive stage, yields decline when day time high temperatures exceed 30°C to 34°C [29]. Increasing temperature causes the maize life cycle and duration of the reproductive phase to be shortened, resulting in decreased grain yield [30, 31]. In the analyses of Muchow *et al*. [31], the highest observed grain yields occurred at locations with relatively cool temperatures (18.0 to 19.8°C), which allowed long maize life cycles, compared to warmer sites (21.5 to 24.0°C), or compared to warm tropical sites (26.3 to 28.9°C). Maximum temperatures are affected by local conditions, especially soil water content and evaporative heat loss as soil water evaporates [32]. Hence, in areas where changing climate is expected to cause increased rainfall or where irrigation is predominant, large increases of maximum temperatures are less likely to occur than will be the case in countries where drought is prevalent. Yield decreases caused by elevated temperatures are related to temperature effects on pollination and kernel set. Temperature above 35°C is lethal to pollen viability [33, 34]. Besides, the critical duration of pollen viability is a function of pollen moisture content, which is strongly dependent on vapor pressure deficit [35]. There is limited data on the sensitivity of kernel set in maize to elevated temperature, although in-vitro evidence suggests that the thermal environment during the endosperm cell division phase is critical [36]. A temperature of 35°C, compared to 30°C during the endosperm division phase, dramatically reduced subsequent kernel growth rate and final kernel size, even if ambient temperature returns to 30°C [36]. Temperatures above 30°C increasingly impaired cell division and amyloplast replication in maize kernels and thus reduced grain sink strength and yield [37]. The positive effects of temperature could be offset by increased variation of precipitation and soil water availability to the crop. At the same time, a longer growing season can affect water availability [38], as well as weed and insect interactions with crops.

Photosynthesis in C_3 plants is more sensitive to higher temperatures compared with C_4 crops [39]. Crops are most sensitive to high temperatures at the reproductive stage and grain-filling/fruit maturation stage [40]. However, plant responses to each type of temperature alteration are species-specific and mediated through both photosynthetic activities for biomass accumulation, which is responsible for plant growth and the phenological and morphological changes, which occur during plant development. Reproductive development in soybean has cardinal temperatures that are somewhat lower than those of maize. A base temperature of 6°C and an optimum temperature of 26°C are commonly used [41], having been derived, in part, from values of 2.5°C and 25.3°C developed from field data by Grimm *et al*. [42]. The post-anthesis phase for soybean has a surprisingly low optimum temperature of about 23°C and the life cycle is slower and longer if the mean daily temperature is above 23°C [43]. This 23°C optimum cardinal temperature for the post-anthesis period closely matches the optimum temperature for a single seed growth rate (23.5°C), as reported [44] and the 23°C optimum temperature for seed size [45, 46]. Increasing air temperature can enable earlier planting if suitable moisture and soil temperature conditions exist, resulting in a longer growing season. A longer growing season creates more time to accumulate photosynthetic products for greater biomass and harvestable yields as long as the temperatures do not exceed optimum values. However, increasing temperatures will also increase crop water demand and larger plants will use more soil water as part of the growth process [38]. As the mean temperature increases above 23°C, seed growth rate, seed size and intensity of partitioning to the grain in soybean decrease until reaching zero at 39°C mean [47]. Pollen viability of soybean is reduced if temperatures exceed 30°C (optimum temperature) but have a long decline slope to failure at 47°C [48]. Soybean grown at 38/30°C versus 30/22°C (day/night) temperatures indicated that the elevated temperature reduced pollen production by 34%, pollen germination by 56% and pollen tube elongation by 33% [48]. The progressive reduction in seed size above 23°C, along with a reduction in fertility above 30°C, results in a reduction in seed harvest index at temperatures above 23-27°C [45, 46]. Zero seed harvest index occurs at 39°C [46]. The implication of a temperature change on soybean yield is thus strongly dependent on the prevailing mean temperature during the post-anthesis phase of soybean.

Extremely high temperatures above 30°C can do permanent physical damage to plants and, when they exceed 37°C, can even damage seeds during storage. The type of damage depends on the temperature, its persistence and the rapidity of its increase or plants' capacity to adjust [28]. It also depends on the species and the stage of plant development. As the climate changes, the frequency of periods when temperatures rise above critical thresholds for maize, rice and wheat is predicted to increase worldwide [49]. The optimum temperature for photosynthesis in wheat is 20-30°C [50]. This is 10°C higher than the optimum (15°C) for grain yield and single grain growth rate [51]. The Grain-filling period of wheat and other small grains shortens dramatically with rising temperature [52]. Any increase in temperature beyond the 25-35°C range that is common during grain filling of wheat will reduce the grain filling period and, ultimately, yields. Lawlor and Mitchell [53] stated that a 1°C rise would shorten the reproductive phase by 6%, grain filling duration by 5% and would reduce grain yield and harvest index proportionately. Chronic effects of warmer temperatures on crop growth and development are probably more important than extreme effects in projecting climate change impacts. Crop yields reflect the importance of season-long effects, where crops generally have a greater yield when the temperature is cooler during the growth of the harvested component. Assuming no difference in daily photosynthesis, which can be inferred from the sink removal studies of Sofield *et al*. [54], the yield will decrease in direct proportion to the shortening of the grain filling period as temperature increases. This temperature effect is already a major reason for the much lower wheat yield potential, even with the water limitation removed. Bender *et al*. [55] analyzed spring wheat grown at nine sites in Europe and found a 6% decrease in yield per 1°C temperature rise. Global mean wheat yield decreased by 5.4% per 1°C increase in temperature [56]. Effects of rising temperature on photosynthesis should be viewed as an additional reduction factor on wheat yield, primarily influenced via water deficit effects [57]. Temperatures of 36/31°C (maximum/minimum) for two to three days before anthesis causes small unfertilized kernels with symptoms of parthenocarpy – that is, small shrunken kernels with notching and chalking of kernels [58].

The increase in average temperature during the growing season typically causes plants to use more energy for respiration for their maintenance and less to support their growth. With a 1°C increase in average temperatures, yields of the major food and cash crop species can decrease by 5 to 10% [40, 56]. With higher average temperatures plants also complete their growing cycle more rapidly [40]. With less time to reproduce, reproductive failures are more likely and this will also lower yields [59]. The response of rice to temperature has been well studied [60-62]. Leaf-appearance rate of rice increases with temperature from a base of 8°C, until reaching 36-40°C, the thermal threshold of survival [61, 63], with biomass increasing up to 33°C [64]; however, the optimum temperature for grain formation and yield of rice is lower (25°C) [61]. Baker *et al*. [61] summarized many of their experiments from sunlit-controlled-environment chambers and concluded that the optimum mean temperature for grain formation and grain yield of rice is 25°C. They found that grain yield is reduced about 10% per 1°C temperature increase above 25°C, until reaching zero yields at 35-36°C mean temperature, using a 7°C day/night temperature differential [60, 65]. Declining yield above 25°C is initially attributed to shorter grain filling duration [66] and then to progressive failure to produce filled grains – the latter is caused by reduced pollen viability and reduced production of pollen [67-69]. Pollen viability and production begin to decline as the daytime maximum temperature exceeds 33°C and reaches zero at a maximum temperature of 40°C [67]. Because flowering occurs at mid-day in rice, the maximum temperature is the best indicator of heat stress on spikelet sterility. Welch *et al*. [70] found this to be the case for a historical analysis of rice in Asia– higher minimum temperatures reduced yields, while higher maximum temperature raised yields; notably, the maximum temperature seldom reached the critical optimum temperature for rice. The grain size of rice tends to hold mostly constant, declining only slowly across increasing temperature, until the pollination failure point [60]. Screening of rice genotypes and ecotypes for heat tolerance (33.1/27.3°C versus 28.3/21.3°C mean day/night temperatures) by Prasad *et al*. [69] demonstrated significant genotypic variation in heat tolerance for percent filled grains, pollen production, pollen shed and pollen viability.

Each type of temperature stress has a different effect on crop duration and overall plant productivity. The effect will depend on how sensitive each species is at their stage of development when the temperature alteration occurs. Adapting to these effects will require different types of responses. The base and optimum temperatures for vegetative development are 8°C and 34°C, respectively [71], while the optimum temperature for reproductive development is 31°C [72]. Another study indicated that the optimum temperature for sorghum vegetative growth is between 26°C and 34°C and for reproductive growth 25°C and 28°C [73]. Maximum dry matter production and grain yield occur at 27/22°C [74]. Grain filling duration is reduced as temperature increases over a wide range [72]. Nevertheless, as temperature increased above 36/26°C to 40/30°C (diurnal maximum/minimum), panicle emergence

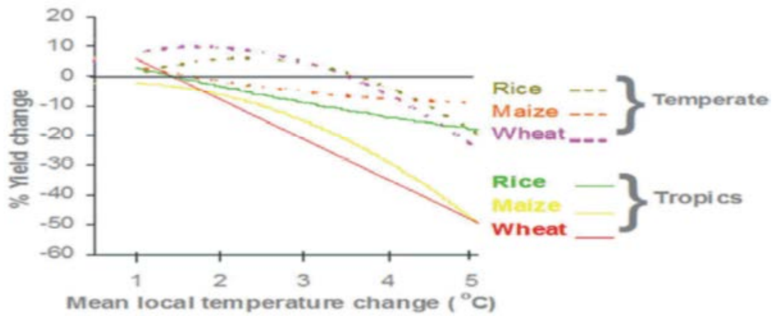

Fig. 2: Comparison of temperature rise on crop yields in temperate and tropical regions. Source: [76]

was delayed by 20 days and no panicles were formed at 44/34°C [72]. Research tends to focus on the effects of average air temperature changes on crops; however, minimum air temperature changes may be of greater importance [75] because minimum temperatures are more likely to be increased by climate change over broad geographic scales [75]. Minimum air temperatures affect night time plant respiration rate and can reduce biomass accumulation and crop yield [40]. Grain yield, harvest index, pollen viability and percent seed-set were highest at 32/22°C and progressively reduced as temperature increased, falling to zero at 40/30°C [72]. Vegetative biomass was highest at 40/30°C and photosynthesis was high up to 44/34°C. Seed size was reduced above 36/26°C. Rice and sorghum have the same sensitivity of grain yield, seed harvest index, pollen viability and success in grain formation [72]. Basing the yield response of sorghum only on the shortening of filling period [51], the yield would decline 7.8% per 1°C temperature rise from 18.5-27.5°C (9.4% yield reduction for a 1.2°C increase). However, if site temperature is cooler than optimum for biomass/photosynthesis (27/22°C), then yield loss from a shorter filling period would be offset by photosynthesis increase. Yield change due to temperature variations in some major crops in temperate and tropical regions are indicated in Figure 2.

Carbon Dioxide: Atmospheric CO_2 concentration has reached 381 ppm today, from a low level of 280 ppm in 1750 AD. It is now rising at a rate of 1.8-2.0 ppm per year [76]. Plant response to elevated CO_2 alone, without climate change, is positive and was reviewed extensively by the IPCC [15] among others. The effects of elevated CO_2 on plant growth and yield will depend on species, photosynthetic pathways (C_3 and C_4 plants have enzymaticdifferences for carbon fixation) and growth stage and management regime, such as water and nitrogen applications. An increase in atmospheric CO_2 has a fertilization effect on crops with a C_3 photosynthetic pathway and thus promotes their growth and productivity. The C_4 crops are not known to significantly benefit from further CO_2 increases. On average, across several species and under unstressed conditions, compared to current atmospheric CO_2 concentrations, crop yields increase at 550 ppm. CO_2 in the range of 10-20% for C_3 crops (e.g. rice, wheat) and 0-10% for C_4 crops (e.g. maize, sugarcane, sorghum). Yields of wheat, rice and soybeans under field conditions increased approximately 12% to 15% under 550 ppm compared with 370 ppm CO_2 concentrations, with the percentage increases about 1.6 times those for elevated CO_2 concentrations of approximately 700 ppm. As compared with most other annual crop species, cotton had an exceptional 43% yield increase under increased CO_2 concentrations, but it should be noted that some varieties of rice and soybean also had yield increases as large as cotton. Maize had negligible yield increases. Within C_3 species, we might expect differences in CO_2 responsiveness between sexual and vegetative commodities and between roots and shoot crops. However, given the variation in response among varieties within species, these expected differences in response have not been substantiated. Also, response differences may exist between annual and perennial species because the stimulation of growth by perennial species grown with little competition may be cumulative over years.

The effect of an increase in CO_2 concentration tends to be higher in C_3 plants (wheat, rice, cotton, soybean, sugar beets and potatoes) than in C_4 plants (corn, sorghum, sugarcane) because photosynthesis rates in C_4 crops are less responsive to increases in ambient CO_2 [77, 78]. The highest fertilization responses have been observed in tuber crops, which have a large capacity to store extra carbohydrates in below ground organs [79, 80]. Reviews of the early enclosure CO_2 studies indicate a 33% increase in average yield for many C_3 crops under a doubling CO_2 scenario [81] at a time when doubling meant an increase from 330 to 660 parts per million (ppm) CO_2.

The general phenomenon was expressed as increased numbers of tillers-branches, panicles-pods and numbers of seeds, with minimal effect on seed size. The C_4 species response to doubling of CO_2 was reported by Kimball [81] to be 10%. High-temperature stress during reproductive development can negate CO_2's beneficial effects on yield, even though total biomass accumulation maintains a CO_2 benefit [82]. Unrestricted root growth, optimum fertility and excellent control of weeds, insects and disease are also required to maximize CO_2 benefits [83]. Most C_3 weeds benefit more than C_3 crop species from elevated CO_2 [84]. Elevated atmospheric CO_2 can modify the responses of crops to environmental stresses. Some modifications tend to reduce effects of stress, such as elevated CO_2 causing partial stomatal closure and reducing the penetration of ozone into leaves, which in turn lowers yield losses due to ozone [85, 86]. Partial stomatal closure at elevated CO_2 also reduces crop water loss [87-89]. However, elevated CO_2 increases crop tissue temperatures, which may exacerbate damage to reproductive processes caused by high air temperatures.

Increased CO_2 also results in increased water use efficiency of all crops. Under field conditions, however, response to enhanced CO_2 is moderated by other environmental constraints. Long *et al*. [90] have shown that the yield enhancement with high CO_2 is only to the extent of 10-15% in field-grown cereal crops, as against the 20-30% response documented earlier [91]. Using a crop model, Aggarwal [92] showed that the benefit of enhanced CO_2 was moderated by nutrient and water constraints in wheat. Rising CO_2 concentration in the atmosphere can have both positive and negative consequences. Maize, being a C_4 species, is less responsive to increased atmospheric CO_2. Single leaf photosynthesis of maize shows no effect of CO_2 on quantum efficiency, but there is a minor increase in leaf rate at light saturation (3% for 376 to 542 ppm; [93]). King and Greer [94] observed 6.2% and 2.6% responses to increasing CO_2 from 355 to 625 and 875 ppm, respectively, in a 111-day study. The mean of the two levels gives about a 4.4% increase to doubling or more of CO_2. A higher concentration of CO_2 in the atmosphere will have different effects on different crops. In C_3 plants, photosynthesis relies on the concentration of CO_2 that is naturally available in the atmosphere. A higher concentration of CO_2 in the atmosphere will have a small fertilizing effect on these crops if all other factors remain favorable. Adverse moisture conditions during the growing season, insufficient nitrogen availability, or temperatures above the optimum range may offset this effect. However, the nutritional content of leaves, stems, roots, fruits and tubers of C_3 plants grown at elevated CO_2 levels is expected to be lower particularly in protein, minerals and trace elements, such as zinc and iron [95, 96]. Plants grown at higher concentrations of CO_2 have lower stomatal conductance and transpiration. This means that plants absorb less water and nutrients and that their biomass becomes less nutritious. One insidious aspect associated with the nutritional quality of crops is that, in addition to humans, also insect pests will have to compensate by eating more to meet their nutritional needs [40]. C_4 plants can increase the CO_2 concentration within their leaves before the photosynthesis begins. This is why increased concentrations of CO_2 in the atmosphere will not provide benefits to C_4 plants under normal conditions. Under moisture stress conditions, however, most C_4 crops will lose less moisture and their yield will be affected less [27]. Ziska and Bunce [97] reported a 2.9% increase in biomass when CO_2 was increased from 371 to 674 ppm during a 33-day, glasshouse study. Maroco *et al*. [98] reported a 19.4% biomass increase when CO_2 was increased from 350 to 1, 100 ppm during a 30-day growth period at very high light for a short duration on young plants. Thus, 4% increases in both biomass and grain yield of maize are possible, with an increase in CO_2 from 350 to 700 ppm. This is less than the simulated 10% increase for C_4 species to incremental CO_2 increases (330 to 660 ppm) [99]. Sorghum, another important C_4 crop, gave 9, 34 and 8% increases in leaf photosynthesis, biomass and grain yield, respectively, with doubling of CO_2 when grown in 1-by-2-meter, sunlit controlled-environment chambers [72].

Elevated CO_2 increases the size and dry weight of most C_3 plants and plant components. Relatively more photoassimilates are partitioned into structural components (stems and petioles) during vegetative development to support the light-harvesting apparatus (leaves). Soybean is a C_3 legume that is quite responsive to CO_2. Based on the metadata summarized by Ainsworth *et al*. [100], soybean response to a doubling of CO_2 is about 39% for light-saturated leaf photosynthesis, 37% for biomass accumulation and 38% for grain yield. Allen and Boote [101] reported a response of 34% in sunlit controlled-environment chambers to increases in CO_2 from 330 to 660 ppm. Ainsworth *et al*. [100] found that under similar conditions, leaf conductance was reduced by 40%, which is consistent with other C_3 and C_4 species [102] and seed harvest index was reduced by 9%. Crop models can be used to project yield responses to CO_2 increase from past to present and future levels. Simulations by Boote *et al*. [103] suggested that soybean yield would have increased 9.1% between 1958 and 2000, during which time the CO_2 increased from 315 to 370 ppm; thus some of the past yield trends of soybean was associated with global change rather than technological innovation. The harvest index tends to decrease with increasing CO_2 concentration and temperature. The selection of plants that could partition more photoassimilates to reproductive growth should be a goal for future research. As more is learned about the effects of anticipated climate changes on crops, more effort should be directed to exploring biological adaptations and management systems for reducing these impacts on agriculture and humanity.

The impact of elevated CO_2 varies according to temperature and availability of water and nutrients. Yield enhancement by elevated CO_2 is limited under both low and high temperature [104, 105]. Theory suggests that water-stressed crops will respond more strongly to elevated CO_2 than well-watered crops, because of CO_2-induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems. For wheat, a cool-season cereal, doubling of CO_2 (350 to 700 ppm) increased light-saturated leaf photosynthesis by 30-40% [106] and grain yield by about 31%, averaged over many data sets [107]. There is observational evidence, that the response of crops to CO_2 is genotype-specific [108]. For example, yield enhancement at 200 ppm additional CO_2 ranged from 3 to 36% among rice cultivars [105]. For rice, doubling CO_2 (330 to 660 ppm) increased canopy assimilation, biomass and grain yield by about 36, 30 and 30%, respectively [62]. Baker and Allen [60] reported a 31% increase in grain yield, averaged over five experiments, with an increase of CO_2 from 330 to 660 ppm. Rice shows photosynthetic acclimation associated with a decline in leaf nitrogen concentration and a 6-22% reduction in leaf Rubisco content per unit leaf area [109]. For peanut, awarm-season grain legume, doubling CO_2 increased light-saturated leaf photosynthesis, total biomass and pod yield of peanut by 27, 36 and 30%, respectively [110]. Doubling CO_2 (350 to 700 ppm) increased light-saturated leaf photosynthesis, biomass and seed yield of the dry bean by 50, 30 and 27% [111]. For cotton, a warm-season non-legume, doubling CO_2 (350 to 700 ppm) increased light-saturated leaf photosynthesis, total biomass and boll yield by 33, 36 and 44% [112], respectively and decreased stomatal conductance by 36% [113]. Under well-watered conditions, leaf and canopy photosynthesis of cotton increased about 27% with CO_2 enrichment, to 550 ppm CO_2 [114]. Mauney *et al*. [115] reported 37 and 40% increases in biomass and boll yield of cotton with CO_2 enrichment to 550 ppm. Even larger increases in yield and biomass of cotton were obtained under the same enrichment for cotton under water-deficit situations [116]. Elevated CO_2 causes greater sensitivity of fertility to temperature in rice [67, 68], sorghum [72] and dry bean [111]. For rice, the relative enhancement in grain yield with doubled CO_2 decreases and goes negative as maximum temperature increases in the range 32-40°C [67]. Likewise, the relative CO_2 enhancement of grain yield of soybean [45] lessened as temperature increased from optimum to super-optimum. In the case of rice, sorghum and dry bean, failure point temperature is about 1-2°C lower at elevated CO_2 than at ambient CO_2. This likely occurs because elevated CO_2 causes warming of the foliage [111]; doubled CO_2 canopies of soybean were 1-2°C warmer [117]; doubled CO_2 canopies of sorghum averaged 2°C warmer during the daytime period [72]. The higher canopy temperature of rice, sorghum and dry bean adversely affected fertility and grain-set. In cotton, there was progressively greater photosynthesis and vegetative growth response to CO_2 as temperature increased up to 34°C [113], but this response did not carry over to reproductive growth [113]. The reproductive enhancement from doubled CO_2 was the largest (45%) at the 27°C optimum temperature for boll yield and there was no beneficial interaction of increased CO_2 on reproductive growth at elevated temperature, reaching zero boll yield at 35°C [113]. Mitchell *et al*. [118] conducted field studies of wheat grown at ambient and +4°C temperature differential and at elevated versus ambient CO_2. While interactions of CO_2 and temperature did not affect yield, higher temperatures reduced grain yield at both CO_2 levels such that yields were significantly greater at ambient CO_2 and ambient temperature compared to elevated CO_2 and high temperature. Batts *et al*. [119] similarly reported no beneficial interactions of CO_2 and temperature on wheat yield; peanut [110]; dry bean [111]. The temperature-sensitivity of fertility (grain-set) and yield for sorghum was significantly greater at elevated CO_2 than at ambient CO_2 [72], thus showing a negative interaction with temperature associated with fertility and grain-set, but not photosynthesis.

When plants are young and widely spaced, increases in leaf area are approximately proportional to the increases in growth and transpiration increases accordingly. More importantly, the duration of leaf area will affect total seasonal crop water requirements.

Thus, the lengthening of growing seasons due to global warming likely will increase crop water requirements. On the other hand, for some determinate cereal crops, the increasing temperature can hasten plant maturity, thereby shortening the leaf area duration with the possibility of reducing the total season water requirement for crops. Elevated CO_2 causes partial stomatal closure, which decreases conductance and reduces the loss of water vapor from leaves to the atmosphere. The effects of elevated CO_2 on stomatal conductance from chamber-based studies have reported that, on average, a doubling of CO_2 (from about 340 to 680 ppm) reduces stomatal conductance by about 34% [120]. Morison [102] calculated an average reduction of about 40%, with no difference between C_3 and C_4 species. Wand *et al*. [121] performed a meta-analysis on observations reported for wild C_3 and C_4 grass species and found that with no stresses, elevated CO_2 reduced stomatal conductance by 39 and 29% for C_3 and C_4 species, respectively. The stomatal conductance of woody plants appears to decrease less than that of herbaceous plants in elevated CO_2, as indicated by an 11% reduction in the meta-analysis of woody plant data by Curtis and Wang [122]. Ainsworth *et al*. [100] found an average reduction of about 40% in conductance of soybean for a wide range of CO_2 concentrations, with the reduction for a doubling being about 30%. A meta-analysis by and of data generated by free-air CO_2 enrichment experiments, for which the daytime concentrations were 550-600 ppm, versus ambient concentrations of about 360 ppm, produced an average reduction in stomatal conductance of 20 and 22%, respectively [123, 124]. They did not detect any significant difference between C_3 and C_4 species. However, as plants shift from vegetative to reproductive growth during their life cycles, proportionately more of the accumulating biomass is partitioned to other organs, such as developing grain. At this point, leaf area and biomass accumulation are no longer proportional. Also, as plants grow and leaf area index increases, the mutual shading and interference among the leaves within a plant canopy cause plant transpiration to plateau [125-127]. Further, considering that a doubling of CO_2 from present-day levels is likely to increase average C_3 species growth on the order of 30% [91, 128], so projecting out 30 years to a CO_2 concentration of about 440 ppm suggests increases in C_3 plant growth only on the order of 10%. Changes in cereal production in developed and developing countries due to increasing CO_2 is indicated in Figure 3.

Precipitation: Like temperature, precipitation and water availability is central to agriculture, with productivity being optimal at a particular water balance. If this is decreased or increased, then productivity will decrease. Although an increase in global average precipitation is projected, this will be highly variable with certain regions experiencing prolonged droughts and/or extensive heavy rainfall. Precipitation has a direct influence on agriculture and is projected to increase for some areas and decrease for others. Changes in the timing, intensity and amount of rain/snow mix for a location are expected to increase the management challenge of delivering water to crops at the right time through irrigation systems and practices. Excess precipitation can be as damaging as the receipt of too little precipitation due to the increase in flooding events, greater erosion and decreased soil quality. Increases in evapotranspiration can result in less available water even in cases when precipitation amounts increase, particularly in soils with limited soil water holding capacity. For example, excess water during maize's early growth stages may cause a reduction in growth or even death, while soil water deficit may lead to less growth and

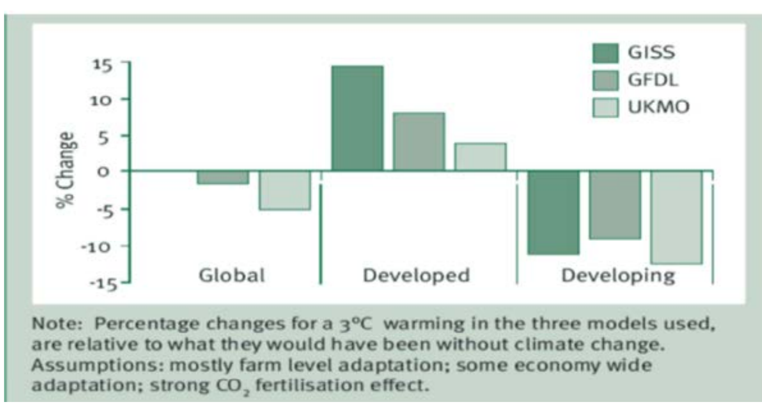

Fig. 3: Change in cereal production in developed and developing countriesfor a doubling of CO_2 levels

lower yields if the stress occurs during the grain filling period of growth [129]. Generally, increased precipitation would probably result in a greater risk of erosion, but could provide the soil with better hydration, depending on the intensity of the rain. Soil erosion increases in regions with increased frequency and severity of rainfall, particularly in winter. Nutrient leaching may increase, but likewise, salt levels in soil may increase due to drought. The interactions between climate change, water scarcity and declines in agricultural productivity could lead to tensions and even open conflict between farmers already struggling with inadequate water supplies due to rising populations and over-pumping of groundwater. Another expected impact of climate change is an increased occurrence of extreme weather events. Even where mean values for precipitation are not projected to change, there are likely to be more significant extreme weather events that will reduce crop yields. Heavy rain, hail storms and flooding can physically damage crops. Extremely wet conditions in the field can delay planting or harvesting. Prolonged droughts can cause complete crop failure [130].

Changes in precipitation regimes include changes in seasonal mean, the timing and intensity of individual rainfall events and the frequency and length of droughts. Each of these factors is critical to crop productivity. The impact of changes in precipitation will be particularly marked when they are combined with temperature alterations that affect the crop's evaporative demands. This may lead to different forms of moisture stress depending on the phenological stage the crop has reached. With 70% of the global water withdrawals and 90% of the global water consumption, the irrigation sector is the dominant water use sector at the global scale. According to an FAO projection of agriculture in developing countries [131], the developing countries would like to expand their irrigated area by 20% by 2030. Most of this expansion will occur in already water-stressed areas, such as South Asia and North Africa. Such an analysis does not consider increased irrigation requirements due to the global-warming associated increase in evaporative demand. Doll [132] projected a significant change in the net irrigation requirements for the global scale due to climatic changes. Depending on the emissions scenario and climate model, global net irrigation requirements were found to increase by 1-3% until 2025 and by 2-7% until 2075. Fischer *et al.* [133] computed increases in global net irrigation requirements of 20% by 2080, with large spatial variations. Predicted increased variability of precipitation, which includes longer drought periods, would also lead to an increase in irrigation requirements, even if the total precipitation during the growing season remained the same [134]. The above results show that irrigation requirements may increase in the future. In contrast, we can expect in the future a scenario of reduced water supply for agriculture due to the effects of global climatic changes on the hydrological cycle, increasing competition from industry/urban areas and currently declining trends of groundwater tables. Production of an increased quantity of food with decreasing availability of quality irrigation water would, therefore, be a big challenge for the agricultural community.

Availability of water is the major limiting factor in the growth and production of crops worldwide. The specific impacts of changes in precipitation regimes on crops vary significantly because around 80% of the cropped area is rainfed and produces 60% of the world's food [135]. The levels and distribution of precipitation determine whether a crop can be grown without irrigation and/or drainage, or whether investments in this area are necessary. Plants need adequate moisture, especially during critical stages of germination and fruit development. Irrigation systems have been developed around the world by many countries to ensure crop water supply. However, despite this, large areas remain rainfed. In climate change scenarios, global precipitation is likely to increase, with a large spatial and temporal variation. These changes in precipitation especially increased frequency of heavy rainfall events, would lead to an increased probability of droughts and floods, in turn, affecting food production stability. The general prediction is that, with climate change, areas that already receive high levels of rainfall will receive more and those that are dry will become drier [136]. The reduction in seasonal mean precipitation will have a greater impact on areas with degraded soils. Soils with lower levels of organic carbon retain less water at low moisture potentials. Furthermore, crops grown in nutrient-poor soils, especially those lacking potassium, recover less quickly from drought stress once water is again available [39]. To help their crops use water more efficiently, farmers must pay attention to improving and maintaining soil fertility. Changes in precipitation patterns and amount and temperature can influence soil water content, run-off and erosion, workability, temperature, salinization, biodiversity and organic carbon and nitrogen content [137, 138]. Changes in soil water induced by global climate change may affect all soil processes and ultimately crop growth.

An increase in temperature would also lead to increased evapotranspiration, which may result in the lowering of the groundwater table at some places. Increased temperature coupled with reduced rainfall enhances upward water movement, leading to the accumulation of salts in upper soil layers.

One of the significant impacts of global warming is on water resources. This is due to spatially variable changes in precipitation, increased rate of glacier melt and retreat affecting river water flows, greater evaporation due to increase in temperature and higher water demand. These changes are likely to affect all aspects of agricultural water management including irrigation availability, soil moisture, evapotranspiration and run-off. As rainfall becomes more variable, farmers may no longer be able to rely on their knowledge of the seasonality of climatic variables. Shifting planting seasons and weather patterns will make it harder for farmers to plan and manage production. For example, a later start of the rainy season or an earlier end, or both, reduces the time that crops have to complete their growth cycle and, ultimately, causes yield losses [139]. For photosensitive species, a change in the duration of the rainy season may cause a mismatch between their reproductive cycle, which is determined by day length and the availability of sufficient soil moisture to produce good yields. The balance among precipitation, evaporation, run-off and soil drainage determines soil moisture. Climate variability, inter-seasonal as well as annual, is known to affect water levels in aquifers. Changes in temperature and precipitation associated with global warming will alter recharge to groundwater aquifers, causing shifts in water table levels [1]. An increase in sea levels may also lead to salinity incursion in coastal aquifers. Arnell [140] and Nohara *et al*. [141] simulated the change in a run-off invarious parts of the world under different scenarios of climate change. Their results showed an increased runoff in high latitudes and the wet tropics and decreased run-off in mid-latitudes and some parts of the dry tropics. Consequent declines in water availability are therefore projected to affect some of the areas currently suitable for rainfed crops [15]. The increased melting and recession of glaciers associated with global climate change could further change the run-off scenario. The IPCC in its recent report has shown that glaciers all over the world are receding at a rapid rate [2]. In recent decades, Himalayan glaciers have receded between 2.6 and 2.8 m/ year [142]. Mass balance studies indicate a significant increase in glacial degraded run-off volume in the last decade, from 200 mm in 1992 to 455 mm in 1999 [143].

Weeds: Climate change affects weeds, pests and pathogens. Changes in temperature and precipitation patterns, coupled with increasing atmospheric CO_2, create new conditions that change weed-infestation intensity, insect population levels, the incidence of pathogens and the geographic distribution of many of these pests. Such changes on non-crop species found in agro-ecosystems are indirect effects of climate change. For agriculture, such effects can alter production yields and quality and may necessitate changes to management practices. These indirect effects may also increase farming costs, as additional inputs may be required to manage the influence of weeds, invasive species, insects and other pests. Crop land agriculture, in its simplest arrangement, can be characterized as a managed plant community that is composed of the desired plant species (crops) and a set of undesired plant species (weeds). Many weeds respond more positively to increasing CO_2 than most cash crops, particularly C_3 “invasive” weeds that reproduce by vegetative means (roots, stolons, etc.) [84, 144]. Agronomic weeds reduce food production through competition for light, nutrients and water and by reducing production quality, increasing harvest interference and acting as hosts for other pest vectors. By altering the environment (temperature) or increasing a resource (CO_2), we change not only the growth of an individual, but also the interactions among species and the growth patterns of the entire plant community. Weeds create the highest crop losses globally (34%), with insect pests and pathogens showing losses of 18% and 16%, respectively [145]. The competition between crops and invasive weeds could also be influenced by the effects of rising temperatures on plant physiology [146]. Competition between C_4 weed species and C_3 crops under different climate conditions and CO_2 concentrations may significantly alter crop productivity [147]. For example, a 3°C increase in the average temperature would favor the perennial invasive C_4 weed, which would cause significant yield reductions in various important C_3 crop systems [148-150].

Weed scientists have long recognized that temperature controls weed species success [151]. Thus, warming will affect the dissemination of weeds with subsequent effects on their growth, reproduction and distribution. For invasive plants with tolerances for higher temperatures, which are currently restricted by low temperatures, increasing temperatures could trigger migration [152]. Climate change may also be a factor for the migration of agronomic and invasive weeds [153]. The species with higher mobility would be favored.

Traits that promote seed dispersal over long distances are common in invasive plants [154-156]. Many of the most troublesome weeds in agriculture – both warm-season (C_3) and cool-season (C_4) species – are confined to tropical or subtropical areas [157]; the lower temperature extremes that occur at higher latitudes are inhospitable to many weeds. High-latitude temperature limits of tropical species are set by accumulated degree days [158], while low-latitude limits are determined, in part, by competitive ability to survive at lower temperatures [159]. However, because many weeds associated with warm-season crops originate in tropical or warm temperature areas, the expansion of these weeds may accelerate with warming [160]. Weed species also possess characteristics that are associated with long-distance seed dispersal and it has been suggested [161] that they may migrate rapidly with increasing surface temperatures. Given their similar life histories and growth rates, crops and weeds are likely to have similar responses to drought; consequently, the overall effect of weeds may be reduced because of decreased growth of both crops and weeds in response to water availability [158]. However, the effects of drought are likely to vary widely among crops and weeds.

Elevated CO_2 can reduce yield losses due to weeds for C_3 crops (soybean, wheat and rice), as many agricultural weeds are C_4 species; and the C_3 pathway, in general, shows a stronger response to rising CO_2 levels. However, both C_3 and C_4 weed species occur in agriculture and there is a wide range of responses among these species to recent and projected CO_2 levels [84]. There are only a handful of field studies that have quantified changes in crop yields with weedy competition as a function of rising atmospheric CO_2 [84]. These outcomes were consistent with the known kinetics of the photosynthetic path-way; i.e., plants with the C_4 photosynthetic pathway performed poorly relative to plants with the C_3 photosynthetic pathway as atmospheric CO_2 increased. For example, soybean yield losses from pigweed, a C_4 weed, were reduced from 45% to 30% with rising CO_2 [84]. Conversely, for dwarf sorghum (C_4 crop) and velvetleaf (C_3 weed), yields further reduced as CO_2 increased. However, the interaction of rising CO_2 on crop-weed competition must also consider weed-crop associations where both plant species have the same photosynthetic pathway, a situation that often occurs since agronomic practices tend to select, over time, for weeds with similar morphological and phenological characteristics to the crop. Field grown soybean, elevated CO_2 per se appeared to be a factor in increasing the relative proportion of C_3 to C_4 weedy species with subsequent reductions in soybean yields [162]. For rice and barnyard grass (C_4), increasing CO_2 favored rice, but if both temperature and CO_2 increased simultaneously, the C_4 weed was favored, primarily because higher temperatures resulted in increased seed yield loss for rice. For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species, the decrease in seed yield from weeds may be greater under elevated CO_2 [163].

Research also suggests that glyphosate, the most widely used herbicide, loses its efficacy on weeds grown at CO_2 levels that likely will occur in the coming decades [164]. While many weed species have the C_4 photosynthetic pathway and therefore show a smaller response to atmospheric CO_2 relative to C_3 crops, in most agronomic situations crops compete with a mix of both C_3 and C_4 weeds. Besides, the worst weeds for a given crop are often similar in growth habit or photosynthetic pathway. To date, for all weed/crop competition studies where the photosynthetic pathway is the same, weed growth is favored as CO_2 increases [165]. To control, many studies have, to date, indicated a decline in herbicide efficacy in response to elevated CO_2 and/or temperature for some weed species, both C_3 and C_4 [166, 167].

Insect Pest: Climate change modifies the interactions between plants and their pests in space and over time. Plants weakened by the direct effects of weather stresses are generally more vulnerable to indirect stresses. For example, plants suffering from waterlogging are less resilient to viruses and plants affected by drought are less able to compete with weeds for soil moisture and nutrients [27]. The distribution of insect pests is influenced by temperatures. With global warming, insects, whose body temperature varies with the temperature of the surrounding environment are most likely to move polewards and to higher elevations [168]. Pest distribution will also respond to changes in cropping patterns to cope with climate change. Major insect pests of cereals, pulses, vegetables and fruit crops, which may move to temperate regions, include cereal stem borers, pod borers, aphids and whiteflies [169]. The geographic ranges of insect pests are limited by the presence of the plants upon which they feed and the ability of the insects to survive temperatures. However, through local dispersal and long-distance migration, some insects may reinvade colder regions annually. Insects are capable of withstanding all but the most extreme precipitation events, thus rainfall affects growth and survival principally through increased cloud cover, which can reduce activity and changes in the nutritional quality of the plants upon which insects feed. It is estimated that insect pests, pathogens and weeds result in almost 30% loss in crop production at present. As a worldwide average, yield loss in major crop species due to animal pests and (non-virus) pathogens, in the absence of any physical, biological, or chemical crop protection, has been estimated at 18% and 16%, respectively [145], but weeds produce the highest potential loss (34%). Avoidance of such loss constitutes one of the main sources of sustainability in crop production. Climate change may bring about changes in population dynamics, growth and distribution of insects and pests. Besides having a significant direct influence on the pest population build-up, the weather also affects the pest population indirectly through its effects on other factors like food availability, shelter and natural enemies [170-172]. The extent of crop losses will depend on the geographical distribution of insect pests; the dynamics of the insect population; insect biotypes; the alterations in the diversity and abundance of arthropods; changes in herbivore plant interactions; the activities and abundance of natural enemies; species extinctions; and the efficacy of crop protection technologies.

Climate change will alter potential losses to many pests and diseases. Temperature changes can result in geographic shifts through changes in seasonal extremes. CO_2 and O_3 can either increase or decrease plant disease and can exhibit important interactions [173, 174], suggesting the need for system-specific risk assessment [175, 176]. Plants do not grow in isolation in agroecosystems. Beneficial and harmful insects, microbes and other organisms in the environment will also be responding to changes in CO_2 and climate. Studies conducted in different countries have already documented changes in spring arrival and/or geographic range of many insect and animal species due to climate change [177]. Temperature is the single most important factor affecting insect ecology, epidemiology and distribution, while plant pathogens will be highly responsive to humidity and rainfall, as well as temperature. Generally, increasing air temperature is beneficial to insect pests. As long as upper critical limits are not exceeded, rising temperatures accelerate every aspect of an insect's life cycle and warmer winters reduce winter mortality. Although increased summer temperatures also favor the growth of insect populations, the extension of the growing season has a proportionately greater effect on the damage insects inflict on their host plants [178]. Moreover, pests' greater nutrient demands in early spring and autumn coincide with the planting and fruiting stages– stages that are particularly vulnerable for many crops and critically important for a successful production. Research shows examples of insect phenology advancing faster than previously experienced within a season [179-182]. Some insects spawning multiple generations per season have responded to longer growing seasons by producing more generations per year [183, 184], which, in addition to adding more insects to the environment, can lead to pests developing greater resistance to insecticides [185].

Climate changes are expected to affect the geographic range of specific species of insects and diseases for a given crop-growing region. For example, Cannon [186] has suggested that migratory insects could colonize crops over a larger range in response to temperature increases, with subsequent reductions in yield. The overall positive influence of increasing air temperature on the expansion of insect geographical ranges is well documented in natural systems, although some insects' ranges have shifted and others have contracted [177, 187-189]. Earlier migration and maturation result in successful colonization of habitats that were formerly outside an insect population's range [182]. Projected increases of extreme precipitation events could make pest population outbreaks and crashes more common [190, 191]. Pest outbreaks are often associated with dry years, although extreme drought is unfavorable to insects [190]. Extremely wet years are also unfavorable [192]. Under changing climate, environmental thresholds currently keeping some pests in check may be exceeded because of increased variability, making pest outbreaks likely to become more common as a result of increased climate variability. Phenological shifts and geographical range shifts in interacting species can be synchronous or asynchronous and as a result, may have important consequences on pest population [193-195]. There is currently a clear trend for increased insecticide use in warmer, compared to cooler, higher latitude areas. For example, the frequency of pesticide sprays for control of lepidopteran insect pests in sweet corn currently ranges from 15 to 32 applications per year in Florida [196], to four to eight applications in Delaware [197] and zero to five applications per year in New York [198]. Warmer winters will likely increase populations of insect species that are currently marginally over-wintering in high latitude regions, such as flea beetles, which act as a vector for bacterial Stewart's Wilt, an economically important corn pathogen.

The effects of increased atmospheric CO_2 on insect pests are much more complex than that of increasing temperature because insect performance is highly dependent on the response of the host plant to increased CO_2. This indirect action of CO_2 makes for quite variable interactions between plants and insect pests. The frequently observed higher carbon-to-nitrogen ratio of leaves of plants grown at high CO_2 [83] can require increased insect feeding to meet nitrogen (protein) requirements [199]. However, slowed insect development on high CO_2-grown plants can lengthen the insect life stages vulnerable to attack by parasitoids [199]. Hamilton *et al*. [200] found that early-season soybeans grown at elevated CO_2 had 57% more damage from insects, presumably due in this case to measured increases in simple sugars in leaves of high CO_2-grown plants. Generally, increasing C to N (C: N) ratios in plants under increased enhanced atmospheric CO_2 makes nutritionally poorer forage for insects. However, compensatory feeding can offset an insect's N needs [201, 202] and the addition of N to the soil can also moderate the influence of CO_2 on insect performance by restoring the C: N ratio that is observed in plants under present-day conditions [203]. Nitrogen limitations can cause plants to produce fewer of the secondary metabolites that are involved in developing resistance to insect pests [204], while enhanced CO_2 fixation can increase C-based defenses that reduce the digestibility of a given crop for insects [205]. For example, enhanced CO_2 fixation by soybeans increases leaf toughness, but there is a coincident decrease of a plant's production of N-based com-pounds such as cysteine proteinase inhibitors–proteins that defend soybean from beetles [181]. Although most insects would find a plant with decreased N-based defenses more appealing, some specialized insects that signal on those specific secondary compounds to stimulate feeding will feed less. Evidence also exists that micronutrients are less available with increasing CO_2 [206], which can reduce the quality of plants used for forage. Ultimately the effect of increased CO_2 on insects is quite variable, with some insects growing more slowly and maturing at smaller sizes and others growing more quickly and becoming larger [205].

Plant Pathogen: Increasing temperature may cause plant stress or may decrease plant stress depending on whether a crop is being grown in its optimal range or near a heat-tolerance threshold. Unfortunately, rarely does a single plant-growth or -health factor change as a result of climate change. When a combination of changes exist that result in temperatures, for example, that are no longer ideal for the crop host, this effect can be compounded when the change coincidently favors increased growth, the formation of spores, earlier initial infection, shorter latent periods, or increased rates of disease progression [207]. With non-vector-borne pathogens, plant-pathogen responses to climate change must be considered within the context of a "disease triangle" that involves the pathogen, the host and the environment; together these parts determine whether a disease, itself a process, will occur [208]. With vector-borne pathogens, the vector must be included in the disease triangle, with the microbial pathogen, the host and the vector all interacting separately with the environment [209]. In addition to having the basic components – pathogen, host and vector – as the required drivers of plant disease, plant pathogens and their vectors are influenced by other factors that complicate our ability to predict pathogen movement, incidence, s everity and evolution [210]. Under current climate conditions, even with efforts to manage disease in place, crop losses to pathogens are estimated to be approximately 11% of overall worldwide production [145]. Pathogen growth and reproduction can be evaluated independently about the epidemiological parameters necessary for disease development. These effects have been determined for some pathogenic viruses, fungi and bacteria, leading to weather-based decision-support models designed to address seasonal production issues and disease management protocols [211, 212].

Drought and heat stress may affect the expression of crop resistance genes that would normally protect from pathogens, but even this can be variable within a given host, depending on the resistance genes present. The effectiveness of some plant genes for resistance to virus diseases is known to be temperature sensitive; for instance, the gene for Tobacco mosaic virus (TMV) resistance is markedly reduced in efficacy above 28°C [2013]. This same temperature effect has been observed in transgenic tomato plants containing the same gene [214]. Conversely, some resistance genes are more effective at higher temperatures. One example of this is the wheat geneYr36, which confers resistance to many races of the wheat stripe rust at temperatures between 25°C and 35°C, but loses the resistance at lower temperatures [215]. Similarly, the bacterial blight resistance gene Xa7 restricts disease more effectively at high temperatures than at low temperatures; although the crop and the pathogen are both presents during cool and warm production seasons [216]. Increased temperature decreases the efficacy of plant antiviral resistance mechanisms based on gene silencing, a process by which a plant gene is "turned off" so that it does not respond to the presence of a virus [216]. In the face of climate-related change, cultural control measures are likely to be less reliable in suppressing virus epidemics. Such techniques include planting upwind of virus sources when prevailing wind patterns vary, planting early maturing cultivars or harvesting early to avoid exposure of crops at peak insect vector flight times and manipulation of sowing date to avoid coincidence of peak times for insect vector flights with vulnerable early crop growth [217]. Changes in individual host-plant structure and shift in a range that affect the whole crop population result in significant alterations in microclimate, pathogen dynamics and multi-trophic interactions [218]; these interactions have far-reaching consequences. Range expansion has been predicted for many pathogens, based on models that incorporate changes in crop distribution and requirements for pathogen survival and reproduction [212]. Climate change is also likely to affect the emergence of virus diseases in new encounter scenarios when vulnerable, newly introduced crops or weeds are grown next to indigenous vegetation infected with viruses the new crops had not been exposed to previously. Although such circumstances have been relatively little studied [217, 219], it is well known that viruses with wide host ranges adapt to new plant hosts better than viruses with narrow host ranges [217].

Extreme weather events projected with climate change include episodes of heavy rain with strong winds, in addition to heatwaves and droughts, all of which influence plant pathogen epidemics [217]. Also, the rate of spread of contact-transmitted viruses will be accelerated through greater plant wounding arising from intense storms that feature heavy rainfall, or hail and high winds. Garrett *et al*. [220] provide a framework for considering climate change effects across multiple changing variables, with individual plant responses to single factors such as increased CO_2 or temperature well characterized for many crop plants. Generally, if host-plant survival can be linked to a single factor that overrides all others, then pathogen survival can likewise be linked to this overriding factor. For example, increased plant growth associated with elevated CO_2 can result in a canopy that is more conducive to fungal foliar diseases due to higher humidity occurring at the microclimate level [218]. Information on the influence of changing climate on crop development, physical structure and biochemistry is critical for determining pathogen response. For example, pathogens that require entry via plant stomata are likely to encounter conditions of increased cuticular wax and higher stomatal resistance. Changes in the wax composition will also likely affect plant-pathogen biochemical interactions that influence infection processes. The potential effects of climate change on plant disease recognized that it would most certainly affect plant disease at many levels of complexity, although generalizations would be difficult to make [121]. Yield and quality losses caused by diseases are influenced by 1) the direct consequences of climate change, e.g., increased temperatures, elevated CO_2 concentrations, altered rainfall patterns, drought and greater wind speeds; 2) alterations in areas cropped and ranges of crops grown and 3) changes in vector ranges and activity. These factors alter the geographic ranges and relative abundance of pathogens, their rates of spread, the effectiveness of host resistances, the physiology of host-pathogen interactions, rates of pathogen evolution and host adaptation and the effectiveness of control measures [217]. Generally, the projected impacts of climate change on crop yields in different countries are indicated in Table 1.

Table 1: The projected impacts of climate change on crop yields in 2080 in select countries. Crop yield changes are expressed as percentages of 2000 baseline values and are computed from aggregated crop model results for what, maize, rice and soybean

Country	% Yield change
Argentina	2
Brazil	-4
USA	8
Southwest	-25
India	-29
China	7
South Central	-2
Mexico	-26
Nigeria	-6
South Africa	-23
Ethiopia	-21
Canada	12
Spain	5
Germany	12
Russia	6

CONCLUSION

Changes in food demands, markets and agricultural technologies have led to major changes in the structure and function of agricultural ecosystems around the world. The pace of these changes is expected to increase rapidly in the coming years and the whole agricultural scenario may become quite different in the next 10 to 20 years. Global climatic changes and increasing climatic variability are likely to further exert pressure on agricultural systems and change the balance among the key determinants of crop growth and yield. An integrated assessment of resource use efficiency, ecological services and economic feasibility needs to guide the choices concerning the most appropriate crops and production practices for each specific context and purpose. This must be done not only to safeguard food security but to help reduce the concentration of greenhouse gas in the atmosphere, improve the cycling of nutrients in the soil, maintain an adequate supply of clean water and preserve the protective functions that healthy and self-maintaining agricultural ecosystems provide. All of this will be crucial for coping with the increasing changes and variability of climate. Moreover, efforts to assess the impacts, adaptation measures and vulnerability to climate change in this changing world scenario need to be strengthened.

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