



Climatic changes and their effects on physiological and nutritional status of crop plants: importance and Strategies. A review

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Received: 09 June 2021

Accepted: 05 August 2021

Published: 10 August 2021

ABSTRACT

Climate change represents one of the greatest research challenges currently faced by plant biologists, agronomists and conservation biologists. Greenhouse gas emissions set to continue to rise for the near future. Impact of elevated atmospheric eCO₂ and associated shifts in temperature and precipitation are all expected to impact plant ecophysiology, distribution and interactions with other organisms. Climate change such as drought, flood, high temperature, storm etc. are increased dramatically. Climate change has both direct and indirect impacts on agricultural production systems. Direct impacts include effects caused by a modification of physical characteristics e.g. temperature levels and rainfall distribution on specific agricultural production systems. Indirect impacts are those that affect production through changes on other species such as pollinators, pests, disease vectors and invasive species. These indirect effects can play a major role. They are much more difficult to assess and project given the high number of interacting parameters and links, many of which are still unknown. Climate change influences food security in a very complicated manner, it hampers the agricultural yield directly by means of disturbing the agro-ecological environment and indirectly by putting pressure on growth and circulation of income and consequently, increased the necessity of agricultural products. Impacts of climate change on food security have been calculated in several ways. Consequently, due to climate changes, many regions of cultivated land may become unsuitable for cultivation, and other tropical regions may produce more crops. Temperature instability will also provide more favorable environmental conditions for insect, pests of crops to boost their capacity to stay alive in cold temperatures and then emerge in outbreaks in spring. It is very crucial to observe that in case of food accessibility, all recent calculations for food security and safety have concentrated mainly on the effects of climate change in ways that did not measure the probability of substantial alteration in the rate of climate extremes on crop productivity. The atmospheric eCO₂ levels have been progressing from the 280 ppm, preindustrial reference levels to current global levels exceed now above 400 ppm. Although the increasing concentration of atmospheric eCO₂ is the main driver of harmful anthropogenic. Climate change, it can also improve crop performance by increasing rates of photosynthesis and water use efficiency (WUE), particularly in C₃ plants. The putative positive effect in agriculture is in fact denoted to as the “CO₂ fertilization effect” This effect has already been observed in crop plants and vegetables. However, longer treatments with eCO₂ might lead to photosynthetic acclimation, due to increased soluble sugars leading to an imbalanced C: N ratio, accelerated leaf senescence and/or limited growth rate.

Keywords: Climate change, Elevated carbon dioxide, Environmental factors, Crop yield, Mineral, Protein, Soluble sugar antioxidants, Soil fertility, Soil properties

1. Introduction

Climate change represents one of the greatest research challenges currently faced by plant biologists, agronomists and conservation biologists. Greenhouse gas emissions set to continue to rise for the near future. Impact of elevated atmospheric e CO₂, and associated shifts in temperature and

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precipitation are all expected to impact plant ecophysiology, distribution and interactions with other organisms (Intergovernmental Panel on Climate Change (IPCC), (2014). Agriculture and climate change are internally correlated with each other in various aspects, as climate change is the main cause of biotic and abiotic stresses that have adverse effects on the agriculture of a region. Agriculture is being affected by climate changes in different ways such as, variations in annual rainfall, average temperature, heat waves, modifications in weeds, pests or microbes, global change of atmospheric eCO₂ or ozone level, and fluctuations in sea level. Such combination of varying global climate has driven the attention of scientists, as these variations are imparting negative effects on crop production and compromising food security worldwide. According to some predicted reports, agriculture is considered the most endangered activity adversely affected by climate changes. Arunanondchai *et al.*, (2018), reported that natural systems, human health, and agricultural production have been carelessly affected by devastating environmental changes, with the increasing population, there is a corresponding increase in food demand owing to concerns about the stability of the global environment. Several researches, Noya *et al.* (2018) stated that availability of water, air pollution, and soil fertility have a large influence on agriculture productivity. With abrupt changes in environmental conditions, the harsh impacts on plant productivity are progressing in great intensities owing to direct and indirect effects of abiotic stresses. Vaughan *et al.*, (2018), reported that continuous deforestation and excessive utilization of fossil fuels, may create high concentration of CO₂ has escalated from 280 µmol/l to 400 µmol⁻¹ in the atmosphere. Carbon dioxides concentration will gradually increase up to 800 µmol/l at the end of this century. Vaughan *et al.*, (2018), stated that emission of especially CO₂, gases, is the main factor for the greenhouse effect and warmer average global temperatures. Number of stress spells their impact on daily life, and damage to agricultural crops FAO (2018), mainly estimate the effects of climate change and environmental variation. Agricultural yield is predominantly suffered due to adverse environmental conditions particularly, in the developing countries. Therefore high temperature and excess of CO₂ accumulation forced scientists to devise new strategies to cope with less predictable challenges (Rosenzweig *et al.*, (2014). Accoutrement these disadvantage and guaranteed food security there is a need for production of new climate-smart crop cultivars Wheeler- *et al.*, (2013), reported that plant growth and yield are greatly influenced by abiotic stresses. Under natural climate conditions, plants often experience numerous stresses like water logging, drought, heat, cold, and salinity (Ashraf *et al.*, 2018; Benevenuto *et al.*, 2017). Suzuki *et al.*, (2014) reported that, abiotic factors include UV-B, light intensities, flooding, gas emissions, and physical and chemical factors that induce more stresses. In the 21st average temperature of earth is expected to increase from 2 to 4.5 °C. According to IPCC (2014), the time-span between the 19th and the 21st centuries is considered the period that experienced the most warming (Pachauri *et al.*, 2014). Under extreme rainfall, well cause destructions due to floods whereas the scarcity or the total absence of precipitation for a longer period of time leads to drought stresses (Khan *et al.*, 2016).

The environment of the globe is continuously changing and industrialization is one of the main factors for temperature increase. Due to extreme weather, events the frequency of global warming is expected to increase that ultimately disturb the ecosystem globally (Kanojia, and Dijkwel, 2018). Living organisms e.g. plants, animals, fishes, and humans affected by the extreme environmental conditions. Climate conditions cause a triggered anxiety among everyone therefore; crop yield might be compromised by fluctuations in various environmental factors that can risk food security. Several studies by Lesk, *et al.*, (2016), Altieri, and Nicholls, (2017), reported that developed countries have more vulnerability towards climatic changes by about (8–11%) than developing states. Climate change and food insecurity are the two major issues of the 21st century. Around 815 million people are affected by malnutrition, hindering sustainable development programs to achieve the universal goal of eliminating hunger by 2030 (Richardson *et al.*, 2018). Food security and agricultural yield are considerably affected by the adverse weather. With elevation in temperature, the production of major crops has been reduced evidently around the world (Ito, *et al.*, 2018). FAOSTAT. (2017), reported that population is supposed to grow to about 9 billion in 2050 and food requirement are expected to escalate by about 85%. Climatic influences are worsened by present cropping schemes with low variation and elevated concentration of inputs, and unstable productivity due to environmental changes in crops (Reckling *et al.*, 2018). The increased frequency of drought and heavy rainfall, temperature fluctuations, salinity, and insect pest attacks are anticipated to decrease crop productivity leading to higher threats of

starvation (Dhankher, and Foyer, 2018). Crop adaptability has suffered not only because of temperature variations, but also because of rainfall (Kang *et al.*, 2009). Campbell *et al.*, (2016), Fig. (1).

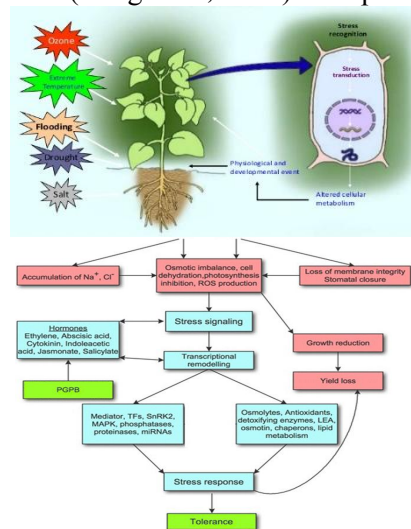


Fig. 1: Overview of salt- and drought-stress responses in plants. Salt and drought affect cell physiology and metabolism and as consequence reduce plant growth. Stress signaling is perceived by the cell and elicits stress-signaling pathways that involve transcriptional remodeling, metabolic changes and altered hormonal activity. Bacterial activity may affect the latter. A positive stress response leads to plant tolerance of the stress while a negative response leads to growth inhibition

Food security and ecosystem resilience are the most concerning subjects worldwide. Climate-smart agriculture is the only way to lower the negative impact of climate variations on crop adaptation, before it might affect global crop production drastically. In this review paper, we summarize the causes of climate change, stresses produced due to climate change, impacts on crops, modern breeding technologies, and biotechnological strategies to cope with climate change, in order to develop climate resilient crops. Revolutions in genetic engineering techniques can also aid in overcoming food security issues against extreme environmental conditions, by producing transgenic plants.

2. Crop Production and Climate Change

Plant physiology has been greatly influenced by climate variability by several means. Environmental extremes and climate variability enhanced the chances of numerous stresses on plants Thornton *et al.*, (2014), Climate change affects crop production by means of direct, indirect, and socio-economic effects as described in Fig. (2) .

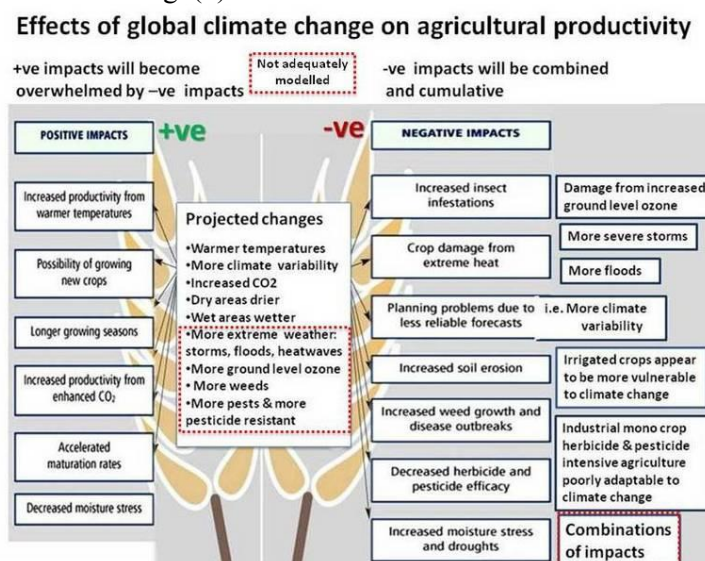


Fig. 2: Diagram illustrates the abiotic stresses that influence crop production

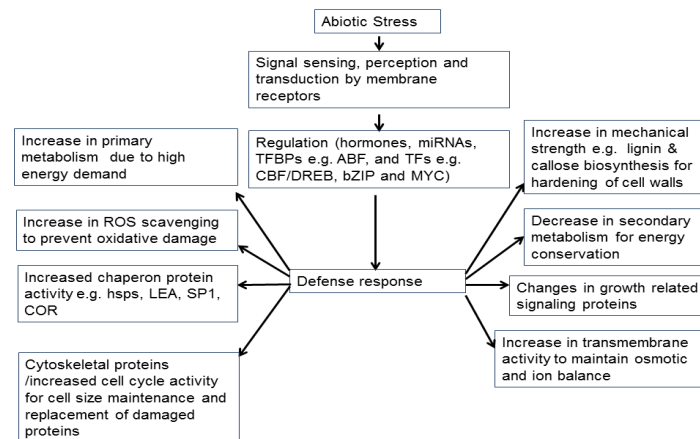


Fig. 3: Illustrates the adverse factors that damage and destroy agricultural crops and you have the impacts that global climate change cause. Most of the lists are factors that cannot be predicted by the computer models the scientists develop and use in assessing the impacts and global warming climate change on agriculture.

Furthermore, climate change such as (drought, flood, high temperature, storm etc.) events are increased dramatically as reported by Food and Agriculture Organization (FAO),2016, reported that climate change has both direct and indirect impacts on agricultural production systems. Direct impacts include effects caused by a modification of physical characteristics such as temperature levels and rainfall distribution on specific agricultural production systems. Indirect effects are those that affect production through changes on other species such as pollinators, pests, disease vectors and invasive species. These indirect effects can play a major role. Much more difficult to assess and project given the high number of interacting parameters and links. Many of which are still unknown Boyer reported in (1982) climate changes have reduced the crop yield up to 70% (Boyer, 1982). Cultivated areas in the world are affected by climatic changes and only 3.5% of areas are safe from environmental limitations (Van Velthuizen, 2007). Whereas the outcomes of abiotic stresses on crop yield are hard to calculate accurately, it is believed that abiotic stresses have a substantial influence on crop production depending on the extent of damage to the total area under cultivation Fig. (3).

In future, the productivity of the major crops is estimated to drop in many countries of the world due to global warming, water shortage, and other environmental impacts (Tebaldi and Lobell, 2018; Bonan, *et al.*, 2018). Based on national crop yields and questionnaire surveys, large differences in vulnerabilities to current climate changes were detected across Europe. In Northern Europe, the short duration for crop development and cool temperature are the major concerns, while the temperature extremes and low rainfall limits the crop productivity in Southern Europe, although the most negative effects will be found for the continental climate in the Pannonian zone, which includes Hungary, Serbia and Romania (Olesen- *et al.*, 2011,2002). It was predicted that the enhancement of greenhouse gas emissions and abrupt climatic changes will occur that may increase the crop yield in North-Western Europe and decrease the crop yield in the Mediterranean area (Olesen *et al.*, 2011).Wheat production is heavily affected by the temperature extremes due to climate change in many countries, and may reduce the crop yield by 6% for each $^{\circ}\text{C}$ rise in temperature (Asseng *et al.*, 2015). Drought and high temperatures are key stress factors with high impact on cereal yields Barnabás *et al.*(2008), Fig.(4) and Rubisco, the central enzyme of photosynthesis, is disrupted if the temperature increases from 35°C , and stops the photosynthetic process (Griffin *et al.*, 2004). Gong *et al.*, (1997) reported the negative effects of heat stress on antioxidant enzymes in *Zea mays*. The combined impact of heat and drought stresses on crop yield has been examined in sorghum, maize, and barley. It was revealed that the combined effect of heat and drought stress had more damaging outcomes as compared to individual stress. Wang and Huang (2004) Xu and Zhou (2006) subjected the *Leymus chinensis* under the combined stresses of drought and heat and found that the function of Photosystem II (PSII) decreased (Xu, *et al.*, 2006).

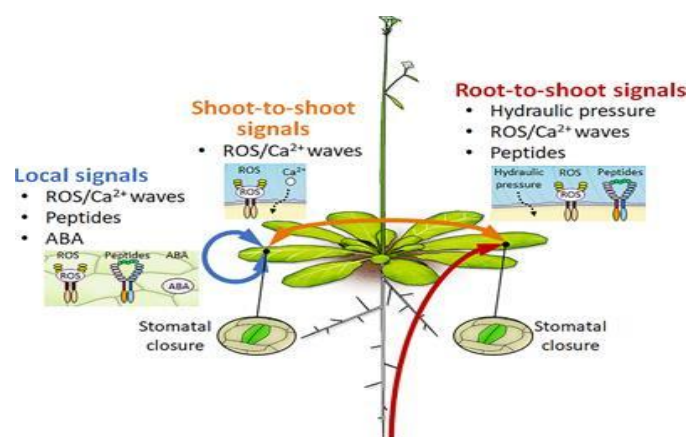


Fig. 4: Conceptual diagram of root-to-shoot, shoot-to-shoot, and local signals in response to drought stress conditions. Mobile signals such as hydraulic pressure, ROS/Ca²⁺ waves, peptides, and phytohormones mediate tissue-to-tissue and long-distance communication for the acquisition of drought stress resistance at the whole-plant level. The red line indicates the root-to-shoot signals such as hydraulic pressure, ROS/Ca²⁺ waves, and peptides signals under dehydration stress conditions. The orange line indicates the shoot-to-shoot signals of ROS/Ca²⁺ waves to mediate stomatal closure under stress conditions. The blue line indicates the local signals of ROS/Ca²⁺ waves, peptide, or ABA signals that mediate stomatal control under stress conditions.

Water deficit and temperature extremes owing to climate change; gradually influence the reproductive phase of plant growth. It was described that the flower initiation and inflorescence is badly affected by the water stress particularly, in cereals crops (Winkel *et al.*, 1997). Climate change led to increment in local and global temperatures pose a significant threat to plant growth and crop production (Priya *et al.*, 2019). The Intergovernmental Panel on Climate Change, 2018 reported that if current rates of global warming continue, global temperatures would continue to increase by a further 1.5 °C between 2030 and 2052. Heat stress can impair all stages of plant growth from germination to reproduction, limiting the productivity of major staple food crops Hussain *et al.*, (2019). For example, heat stress has a negative impact on wheat yields. A 4–6% reduction in average global yields of wheat is predicted for each 1°C increase in global mean temperature (Asseng *et al.*, 2015), Abdelrahman *et al.*, (2020), who place emphasis on the temperature susceptibility of the reproductive and grain-filling stages, and discuss the selection and development of germplasm that can maintain high yields under heat stress, competently review metabolome dynamics in wheat. Plant reproductive organs and processes leading to seed set are extremely vulnerable to increasing temperatures. Lohani *et al.*, (2020) discussed the current knowledge and understanding of the molecular mechanisms that contribute to this temperature sensitivity, they summarized the regulation of male and female reproductive organ development and fertilization, together with heat-induced abnormalities at flowering, (Janni *et al.*, 2020). They evaluate the potential roles of different processes in increasing crop resilience and productivity; describe the importance of genetic mechanisms in the heat stress responses of crop plants. A metabolite profiling analysis of winter wheat genotypes revealed a significant increase in sugars, sugar-alcohols, and phosphate in the more temperature-tolerant genotypes (Impa *et al.*, 2019). Carbon loss caused by high night-time temperatures led to a significant reduction in winter wheat yields (Impa *et al.*, 2019). The study by Sharma *et al.*, (2020) demonstrates that plant growth regulators (PGRs) can afford protection against high-temperature stress (HTS). These authors report that PGR-treated plants were more resilient to heat stress in terms of less damage to membranes, improved photosynthesis and leaf water status, and carbon allocation than the untreated HTS controls (Sharma *et al.*, 2020). Similarly, if the temperature increase of about 30°C during floret development it can cause sterility in cereals (Saini and Aspinall, 1982). During the meiotic phase, wheat and rice suffered from the 35–75% reduction in grain set due to water deficit (Saini, and Aspinall 1981; Sheoran and Saini 1996). In rice, drought stress greatly disturbs the process of fertilization and anthesis. Due to water deficit, the harvest index is reduced to 60% and decreases the grain set (Garrity and O'Toole, 1994). The cocoa yield has been significantly reduced by the major drought spells in West Africa during the 1980s El Niño years (Ruf *et al.*, (2015). It has been estimated that agricultural production could reduce to 25.7% by 2080 due to

climate change and maize will be the most affected crop in Mexico Hellin, *et al.*, (2014). A study based on ECHAM6 climate data were analyzed for North German Plains during two different time durations: 1981–2010 and 2041–2070. The results showed that if the yield for winter wheat is to be sustained, water availability must be guaranteed (Svoboda, *et al.*, 2015). Zhao *et al.*, (2017), they carried out an experiment to analyze the climate change impact on major crop yields and showed considerable yield reductions of 6%, 3.2%, 3.1%, and 7.4% in wheat, rice, soybean, and maize, respectively (Zhao *et al.*, 2017; Scheben, *et al.*, 2016). Drought stress influences wheat during all developmental stages, but grain formation and the reproductive stage are the most critical ones (Pradhan, *et al.*, 2012). Wheat yield was decreased from 1% to 30% during the mild drought stress at post-anthesis while this reduction increased up to 92% in case of prolonged mild drought stress at flowering and grain formation (Araus *et al.*, 2002; De Oliveira *et al.*, 2013).

Drought stress has greatly reduced the yield of important grain legumes. Mash bean (*Vigna mungo* L.) Yield has been decreased by drought stress from 31% to 57% during the flowering stage while a 26% reduction caused by drought stress during the reproductive phase (Baroowa and Gogoi, 2014). Maleki *et al.*, (2013) reported that the soybean yield has been largely affected by drought stress and a 42% reduction was observed during the grain filling stage of soybean (Maleki *et al.*, 2013). Schlenker and Roberts (2009) described that maize yield was increased at an optimum temperature of 29°C but a further increase in temperature hampered the yield of maize (Lobell, *et al.*, 2011). Every 1°C rise in temperature was found to negatively influence the maize yield (Schlenker and Roberts, 2009). Similar results reported by, Lobell, *et al.*, (2011), that yield in maize decreased by 8.3% with every 1°C rise in temperature from the optimum growth temperature. Brown *et al.*, (2009) reported that wheat yield decreased by about 10% with every 1°C increase in temperature (Lobell and Field, 2007). In another report it was reported that a 3–4% reduction in wheat yield takes place for every 1°C increase in temperature (Ray *et al.*, 2015). Easterling *et al.*, (2007) described that a 2°C increase in temperature cause 7% reduction in yield while a further increase in temperature to 4 °C decreased the yield by up to 34% in wheat. Similarly, rice yield decreased by 2.6% for every 1°C rise in temperature (Easterling *et al.*, 2007). In sorghum, yield was reduced by 7.8% due to a 1°C increase in temperature (Kjellstrom *et al.*, 2018). In sorghum, water shortage is another big issue reported in most of the world's top producer countries (Otto *et al.*, 2017). Schlenker and Roberts (2009) revealed that the threshold temperature for soybean is 30 °C; a rise in temperature to the optimum level increased soybean yield but after that level, further rise in temperature reduced the yield abruptly (Schlenker and Roberts, 2009). Eastburn *et al.*, (2010) reported that the rise in ozone and CO₂ concentration in the atmosphere influenced the disease type, and with a continuous rise in temperature, disease susceptibility in soybean was enhanced Eastburn *et al.* (2010). Kitano revealed this rising concern in the growing quantity of research papers focused on abiotic problems after the crucial review on systems biology (Kitano 2002). The amount of research studies has increased dramatically related to biotic and abiotic stresses in plants by applying different strategies Fig. (5).

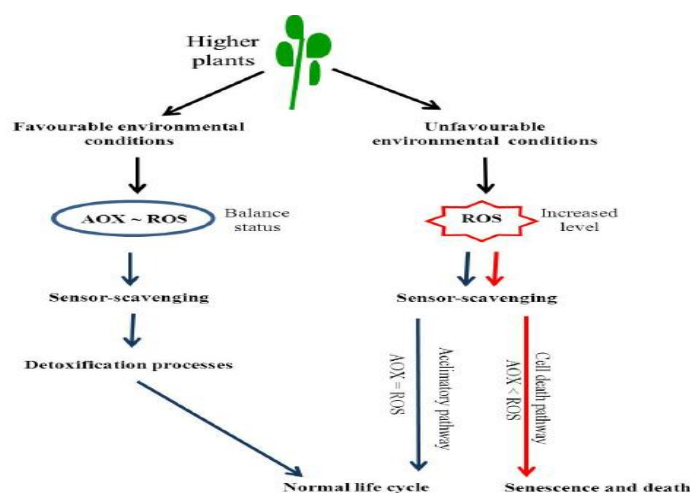


Fig. 5: Represents diagram of antioxidants and redox signaling in plants

Climate change influences food security in a very complicated manner. It hampers the agricultural yield directly by means of disturbing the agro-ecological environment and indirectly by putting pressure on growth and circulation of income and consequently, increased the necessity of agricultural products. Impacts of climate change on food security have been calculated in several ways Intergovernmental Panel on Climate Change (IPCC), (2007). These advances have to be established to tackle amplified rate of climate changes, for example, drought and temperature extremes in the Mediterranean zone or massive rainfall spells and in temperate areas increase the risk of flooding (Schmidhuber, and Tubiello, 2007). Nevertheless, in the case of arid and semiarid regions, it may cause a reduction in livestock growth and enhance their death rates (Intergovernmental Panel on Climate Change (IPCC), 2000). The extensive rate of evapotranspiration and less moisture in the soil are predicted in drier regions by various climate models Intergovernmental Panel on Climate Change (IPCC), (2007).

Consequently, due to climate changes, many regions of cultivated land may become unsuitable for cultivation, and other tropical regions may produce more crops. Temperature instability will also provide more favorable environmental conditions for insect pests of crops to boost their capacity to stay alive in cold temperatures and then emerge in outbreaks in spring. It is very crucial to observe that in case of food accessibility, all recent calculations for food security and safety have concentrated mainly on the effects of climate changes in ways that did not measure the probability of substantial alteration in the rate of climate extremes on crop productivity. They have also not considered the situations of sudden changes in socio-economic status and climate, so all these factors have been putting negative impacts on global food security and safety (Schmidhuber, and Tubiello, 2007). Around the globe, food security is remarkably significant for human beings. Because of climate change, food quality, supply and safety are still the biggest problems for researchers. Future studies on food security will need to incorporate climate change, crop productivity, water supply, and population to estimate food security conditions entirely and scientifically (Kang *et al.*, 2009).

3. Climate Changes as a Global Problem

3.1. Impact on soils

Climate change has become a major scientific and political issue during the last decade. There are well-marked cold and hot cycles in the history of earth's climate, however, these changes have been observed relatively rapid in the last 150-200 years around the world. Fauchereau *et al.*, (2003) reported that soil seems to be more important for modern human societies than ever before to meet the global demands for food and fiber for increasing population from limited soil resources. Climate change is threatening food security globally. Countries like India are more vulnerable in view of the tropical climate and poor coping capacity of the small and marginal farmers. Climate change is projected to have significant impacts on agriculture through direct and indirect effects on crops, soils, livestock and pests. However, climate change is a slow process involving relatively small changes in temperature and precipitation over long period, nevertheless these slow changes in climate influence the various soil processes particularly, those related to soil fertility Fig. (6).

The effects of climate change on soils are expected mainly through alteration in soil moisture conditions and increase in soil temperature and CO₂ levels because of climate change. The global climate change is projected to have variable effects on soil processes and properties important for restoring soil fertility and productivity. The major effect of climate change is expected through elevation in CO₂ and increase in temperature.

3.2. Soil formation and development

Soil formation is controlled by numerous factors including climatic factors such as temperature and precipitation. These parameters of climate influence the soil formation directly by providing biomass and conditions for weathering. Main parameters of climate that directly influence on soil formation are sum of active temperatures and precipitation-evaporation ratio Fig. (7). They determine values of energy consumption for soil formation and water balances in soil, mechanism of organic-mineral interactions, transformation of organic and mineral substances and flows of soil solutions. Stable progressive climate warming lead to irreversible changes in mineral matrix of soils. Changes in external factors of soil formation (temperatures and precipitation) will lead to transformation of internal factors (energy, hydrological, biological). The climate change will increase energy of destruction of soil

minerals resulting in simplification of mineral matrix due to accumulation of minerals tolerant to weathering Fig. (7).

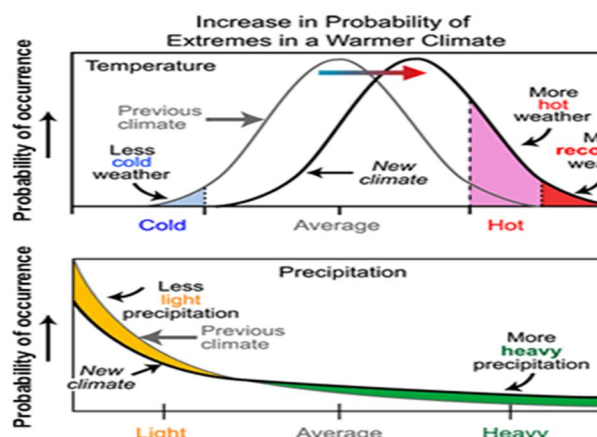


Fig. 6: Illustrates small changes in the global average temperature also mean heat waves get hotter and droughts get drier, the pine forests became sagebrush desert. Such changes in precipitation could be just as important, or even more important, than temperature increases for many parts of Earth.

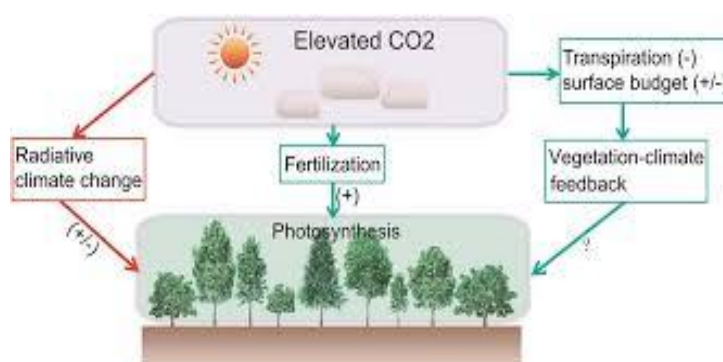


Fig. 7: Schematic diagram of CO₂'s three-pathway influence on terrestrial gross primary productivity (GPP).

The rising atmospheric CO₂ concentration will facilitate plant uptake of CO₂ through photosynthesis (fertilization effect). CO₂ also influences plant photosynthesis indirectly through its climate forcing effect. Its impact on climate through trapping long wave radiation (radiative climate change) can increase Earth's mean surface temperature and thus influence plant photosynthesis. The response of plants to rising CO₂ can cause an increase in foliage cover and decreases leaf transpiration by reducing stomatal conductance per unit leaf area, which also influence climate system (vegetation-climate feedback) and thus influence plant photosynthesis indirectly.

Gross primary productivity (GPP) plays a crucial role in driving the land carbon cycle. Process-based and data driven models have been used to evaluate how global GPP responds to climate change and rising CO₂ concentrations (Beer *et al.*, 2010; Jung *et al.*, 2011; Piao *et al.*, 2013). Models and field experiments agree on the fact that elevated CO₂ increases carboxylation rates and GPP (hereafter fertilization effect) in absence of nutrient limitations and decreases leaf-scale stomatal conductance (Medlyn *et al.*, 2015). The radiative forcing of elevated eCO₂ also causes climate change, which can increase or reduce GPP depending on regional temperature and water limitations, with water limitations being today prominent over most of ecosystems (Beer *et al.*, 2010). Therefore, there are large uncertainties about the magnitude and regional patterns of the net GPP response to the joint perturbation of eCO₂ concentration and climate change (Beer *et al.*, 2010). Most studies of GPP trends with process-based land carbon models have been conducted by using so-called off-line simulations where atmospheric forcing conditions are imposed to an ecosystem model, but there is no feedback from the

land surface to the atmosphere (Piao *et al.*, 2013; Beer *et al.*, 2010). Coupled climate-carbon cycle models include both impacts of CO₂ through climate change and vegetation fertilization, but previous simulations did not fully separate the two mechanisms (Friedlingstein *et al.*, 2006; Arora *et al.*, 2013; Matthews *et al.*, 2007). In a coupled climate-carbon models, climate change affects GPP differently across regions and time of the year, depending upon local temperature or water limitations (Matthews *et al.*, 2007; Cox *et al.*, 2000). In addition, vegetation-climate feedback occurs when plants close their stomates and decreased transpiration under elevated CO₂. This anti-transparent effect of eCO₂ leads to more soil moisture being available for plants in the dry season and changes the partition of net radiation between latent heat (evapotranspiration) and sensible heat. Increases in vegetation cover and leaf area index due to CO₂ fertilization can, however, offset the effect of leaf-level stomatal closure by increasing the surface of leaves available for transpiration (Ukkola *et al.*, 2015; Donohue *et al.*, 2013). Previous research on carbon-climate feedback under eCO₂ mainly focused on the eCO₂-fertilization (a negative feedback on climate change through increased carbon sinks caused by higher GPP) and on eCO₂-induced climate change. Vegetation-climate feedback under eCO₂ have been shown to decrease atmospheric humidity Cao *et al.*, (2010) and precipitation Andrews *et al.*, (2011); Boucher *et al.*, (2009), which warms land surface temperature and in turn impacts GPP. But the effect of climate change from eCO₂ through vegetation-climate feedback on GPP has not been separated from the CO₂-fertilization effect in previous studies. Here we use the terms eCO₂-VCF to denote climate change caused by vegetation-climate feedback under eCO₂ and eCO₂-FERT for the CO₂ fertilization effects on GPP.

It will lead loss of soil function for fertility maintenance and greater dependence of on mineral fertilizers. Soil development is broadly controlled by three main factors i.e. climate, parent material and vegetation type. The effects of climate change on soil development are expected mainly through alteration in soil moisture conditions and increase in soil temperature and CO₂ levels. Climate change will influence soil moisture levels by direct climatic effects (precipitation, temperature effects on evaporation), climate induced changes in vegetation, plant growth rates, rates of soil water extraction by plants and the effect of enhanced CO₂ levels on plant transpiration. Changes in soil water fluxes may also feed back to the climate itself and even may contribute to drought conditions by decreasing available moisture, altering circulation patterns and increasing air temperatures. Among various factors controlling the process of soil development, climate plays a major role in weathering of rocks and minerals. The variables of climate change particularly temperature and rainfall dictates various stages of weathering of rocks and minerals (parent material) resulting in chemical and mineralogical changes in soil forming rocks. Water is very essential for chemical weathering to take place and hence, an increase in rainfall accelerates weathering. The same types of primary minerals give rise to different secondary minerals when the conditions of weathering differ. Thus, similar rock types undergoing weathering in different climatic conditions could give rise to distinct soil profiles.

3.3. Plant nutrients availability, transformation and acquisition

Plant availability of nutrients in the soil is a function of soil chemical properties as well as location of the ion relative to the root surface and the length of the pathway the nutrient must travel in the soil to reach the root surface Fig. (8). Increases in air temperature and changes in precipitation have significant impacts on root zone temperature and moisture regimes. It is well known that soil moisture and temperature are primary determinants of nutrient availability and root growth and development and that carbon allocation to roots governs nutrient acquisition, it is reasonable to expect that process outcomes will be reflective of the changed climate.

The nature and extent of the change in these two parameters will be site- and soils specific. It has been suggested that climate change impacts on nutrient use efficiency is be primarily affected through direct impacts on root surface area and influx rate (Brouder and Volenec, 2008). Plants accumulate nutrients from the soil solution pool, and nutrients must be in solution to be mobile in the soil biological transformation between organic and inorganic pools is strongly influenced by moisture and temperature, and thus, global climate change may strongly influence solution concentrations of N as well as Pendall *et al.*, (2004) who suggested that increased CO₂ may not exert a significant direct effect on N mineralization per use but associated warming can cause increased N mineralization, leading to increased solution-phase N (Abou Seeda *et al.*, 2020). Rates of adsorption/ desorption reactions will accelerate with increased temperature, and changes in soil moisture may further modify reactions by altering the ionic strength of the soil solution.

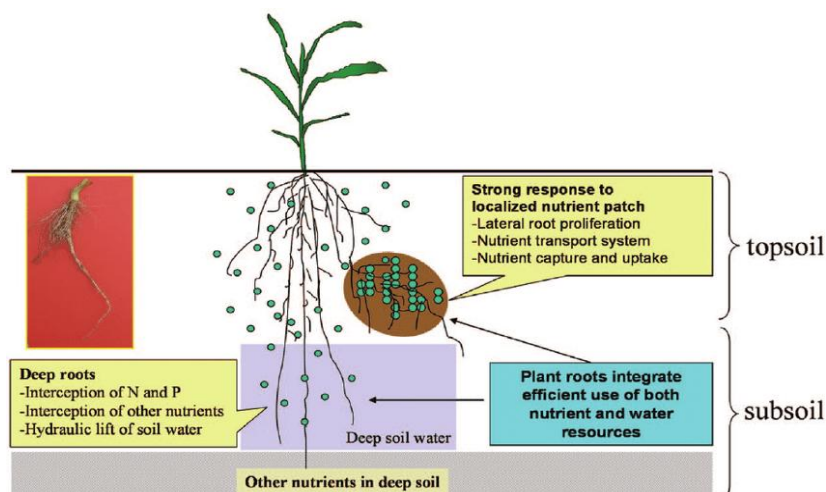


Fig. 8: Represents root architecture with strong responses to localized nutrient patches and deep rooting properties for efficient nutrient and water acquisition. After Mi *et al.*, 2010).

3.4. Adaptation and mitigation strategies

Agriculture can adapt to climate change by adopting farm management practices that minimize the adverse effects of increasing or decreasing rainfall and temperatures or other extreme weather conditions. Many management level adaptation options are available to attenuate the effects of climate change on crop production, including zero tillage, retaining crop residues, extending fallows, increasing the diversity of production, altering amounts and timing of external inputs, as well as broader agronomic management strategies. Agriculture can contribute to climate change mitigation through farm management practices that reduce greenhouse gas emissions and enhance soil carbon sequestration. Emissions of carbon dioxide can be reduced through reduced biomass burning and more efficient energy use. Emissions of methane reduced through improved farm management practices that include improved management of livestock waste and water in rice paddies. Nitrous oxide emissions reduced through improved management of N fertilizers including appropriate type, rate and method of application and soil management. Various farm management practices can enhance soil carbon stocks and encourage soil functional stability. Conservation agriculture technologies, soil conservation measures and nutrient replenishment strategies can restore soil organic matter by providing a protective soil cover and an environment conducive to vigorous plant growth. In some cases, however, a change in the agricultural production system may be required. Continuous cereal cropping is being replaced by ley farming or by the introduction of agro forestry systems. The global soil carbon pool exceeds biomass pools by a factor of four or five, without taking into account that recent soil degradation has led to losses of between 30 percent and 75% of their antecedent soil organic carbon. Globally, therefore, a soil carbon increase offers great mitigation potential. Carbon sequestration refers to the storage of carbon in a stable solid form. It occurs through direct and indirect fixation of atmospheric CO₂. Direct soil carbon sequestration occurs by inorganic chemical reactions that convert CO₂ into soil inorganic carbon compounds such as calcium and magnesium carbonates. Direct plant carbon sequestration occurs as plants photosynthesize atmospheric CO₂ into plant biomass. Subsequently, some of this plant biomass is indirectly sequestered as soil organic carbon (SOC) during decomposition processes. The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms. Many agronomic, forestry, and conservation practices, including best management practices, leads to a beneficial net gain in carbon fixation in soil.

It is generally accepted that increases in CO₂ concentration quantitatively and qualitatively alter the release of root-derived compounds. Plants under elevated CO₂ decrease their allocation of N-rich metabolites and increase the allocation of C rich metabolites to root exudates. Tarnawski and Aragno (2006) stated that such phenomena gradually increase in microbial activity and consequently the CO₂ production, which has is a potential negative effect on the accumulation of organic C in soils and thus on potential sequestration of soils Fig. (9).

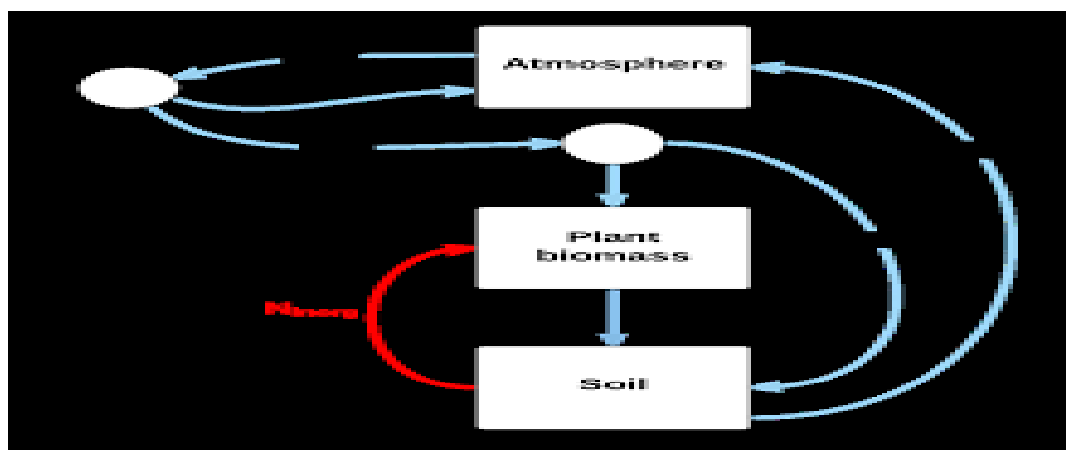


Fig. 9: Representation of the C cycle, including pools (squares), the fluxes of C between pools (blue arrows), and its interaction with the N cycle (red arrow). Circles represent the division of a flux in to two different sub fluxes. Plants absorb CO₂ from the atmosphere via photosynthesis. Part of the photosynthetically fixed C (gross primary production, GPP) goes back to the atmosphere (Ra, autotrophic respiration). The remaining utilizable C (net primary production, NPP; $NPP = GPP - Ra$) can be allocated to biomass productivity (BP, growth), and to Cex (C export, exudation into the soil and allocation to mycorrhizal fungi and root symbionts). When plants die, the C in plant biomass is transferred into the soil C pool. Soil microorganisms, fuelled by the Cex released belowground, can decompose the available soil organic matter (SOM): a process in which N is transformed from organic to inorganic form (mineralization), and hence it can become available to plants to support their growth. The decomposition of SOM emits CO₂ back to the atmosphere (Rh, heterotrophic respiration). After César Terrer-Moreno (2017).

It was stated that the concentration has a significant negative feedback on global change processes and will reduce the sequestration potential of soils. Several studies using C isotope tracers have demonstrated that the production of CO₂ in the rhizosphere by roots and microorganisms is significantly stimulated by elevated CO₂ plant growth conditions. The stimulation of CO₂ respiration in the rhizosphere may be much higher than the enhancement of root biomass. Cheng *et al.*, (1998), demonstrated that although plants produced only 15–26% more biomass under elevated CO₂, rhizosphere respired C increased by 56–74% as compared to ambient CO₂ treatments.

Agro-ecosystems can play an important role in mitigating CO₂ emissions through biotic C sequestration in soils and vegetation. Because of historic losses of C from soils, estimated to be 41 to 55 Gt, the soils now offer an opportunity for carbon storage. The carbon sequestration potential of a soil depends on climate, the type of vegetation it supports, the nature of parent material, the depth of profile, soil drainage, the edaphic environment, soil organic matter (SOM) content and its decomposability and land management practices. Improved management of agro-ecosystems can significantly enhance C sequestration in soils. Management practices or technologies that increase carbon input to the soil and reduce C loss or both lead to net carbon sequestration in soils. Increased C input in agro-ecosystems can be achieved in a number of ways such as selection of high biomass producing crops, residue recycling or residue retention by lessened tillage intensity, application of organic materials e.g. animal manure, compost, sludge, green manure, adoption of agro forestry systems, intensification of agriculture through improved nutrient and water management practices, reducing summer or winter fallow, changing from monoculture to rotation cropping, and switching from annual crops to perennial vegetation. Soil carbon loss could be decreased by adopting conservation agriculture and minimizing soil disturbance, checking erosion through reduced tillage intensity, and using low quality organic inputs. Technological options that have been found to be efficient for soil C sequestration in Indian agro-ecosystems include integrated nutrient management and maturing, crop residue incorporation, mulch farming and/conservation agriculture, agro-forestry systems, grazing management, choice of cropping system and intensification of agriculture. Integrated nutrient management involving addition of organic manures/composts along with inorganic fertilizers results in improved soil aggregation (Benbi and Senapati, 2009).

4. Climatic changes on mineral accumulation and importance

The atmospheric CO₂ levels have been progressing from the 280 ppm preindustrial reference levels, Ainsworth and Long (2005); Myers *et al.*, (2017) to current global levels which are now above 400 ppm, IPCC (2018). Although the increasing concentration of atmospheric CO₂ is the main driver of harmful anthropogenic climate changes, it can also improve crop performance by increasing rates of photosynthesis and water-use efficiency, particularly, in C₃ plants. The putative positive effect in agriculture is in fact denoted to as the “CO₂ fertilization effect” Ainsworth and Long (2005); Bowes (1993); Bunce (2015); Dietterich *et al.*, (2015); Högy and Fangmeier (2008); Loladze (2014); Long *et al.*, 2004; Myers *et al.*, (2017); Ziska and Bunce (2007). This effect has already been observed in crop plants and vegetables, including wheat Dong *et al.*, (2018c); Fernando *et al.*, (2012a); Han *et al.*, (2015); Högy and Fangmeier 2008), maize Zong and Shangguan (2014), rice (Guo *et al.*, 2015; Pang *et al.*, (2006); Yang *et al.*, (2007), barley Haase *et al.*, (2008); Mitterbauer *et al.*, (2017), bean (Bunce (2008); Ma *et al.*, (2017), soybean Bunce (2015); Kumagai *et al.*, (2015), cowpea Dey *et al.*, (2017), potato Kumari and Agrawal (2014), lettuce, carrot, parsley Dong *et al.*, (2018b); Long *et al.*, (2004); Mortensen (1994) and tomato Jin *et al.*, (2009) among others. However, longer treatments with eCO₂ might lead to photosynthetic acclimation, due to increased soluble sugars leading to an imbalanced C: N ratio, accelerated leaf senescence and/or limited growth rate Fig. (10), Ainsworth and Long (2005); Ainsworth *et al.*, (2004); Kaplan *et al.*, (2012); Ludewig and Sonnewald (2000). Future models of climate change for the period of 2000-2100 predicted an overall decrease of the growing season length and crop transpiration, and increase in water-use efficiency, biomass production, and yields, but with considerable variation among crop models (Ahmed *et al.*, 2017; Bassu *et al.*, 2014).

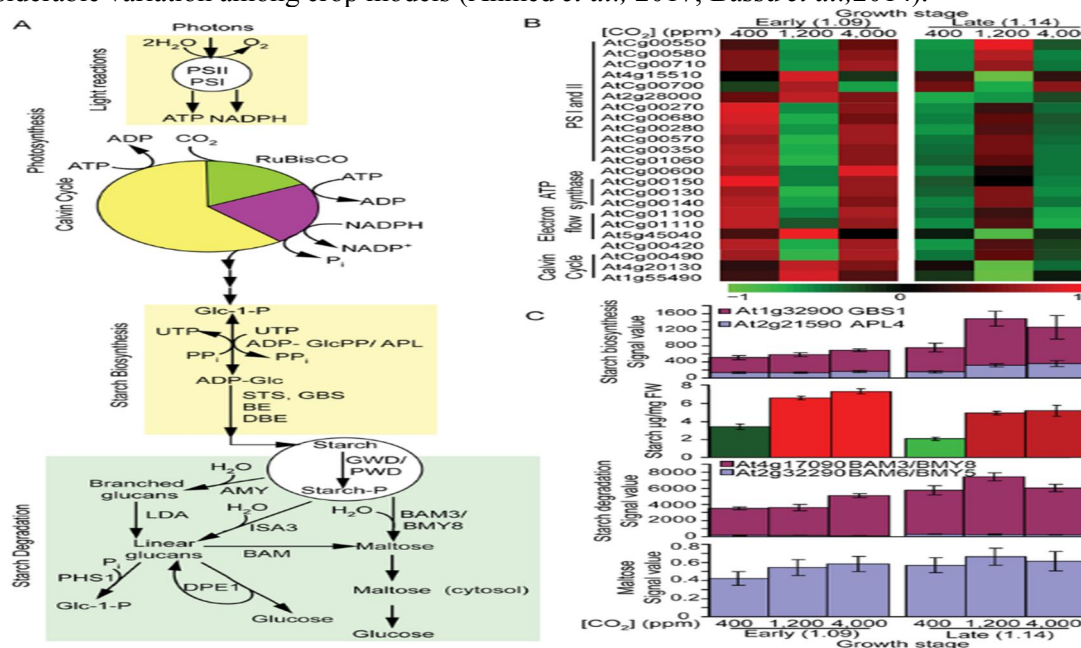


Fig. 10: Illustrates influence of [CO₂] and development on photosynthesis and starch metabolism. A) Photosynthesis and starch biosynthesis and degradation pathways. B) Heat maps of the transcript profiles of photosynthesis. For each gene, its expression level was normalized across all samples so that the mean expression is 0 and the variance is 1. Higher levels are represented with color red of increasing intensity, and lower levels are represented with green of increasing intensity. The increased or reduced expression is relative to the mean expression. All transcript levels shown was statistically significant (p -value ≤ 0.001) with 2 fold or more increase or decrease at any one treatment. C) Starch biosynthesis, starch content, starch degradation and maltose content ($n = 3$ biological replicates $\times 3$ analytical replicates). Starch levels were significantly higher in elevated and SE [CO₂] treatments (students t-test p -value < 0.05) than the control.

Despite all the compelling evidence, there is still insufficient knowledge on the role of eCO₂ in shifting the nutritional composition of crops and on the direct consequences to humans Dong *et al.*, (2018b); Duval *et al.*, (2012); Fernando *et al.*, (2012a); Guo *et al.*, (2015); Högy and Fangmeier (2008); Jablonski *et al.*, (2002); Li *et al.*, (2018b); Loladze (2002); Myers *et al.*, (2014). Loladze (2014) describing a

significant reduction in overall mineral concentration (~8%) in C₃ plants, including foliar and edible tissues using a meta-analysis of FACE and non-FACE studies, Fig. (11).

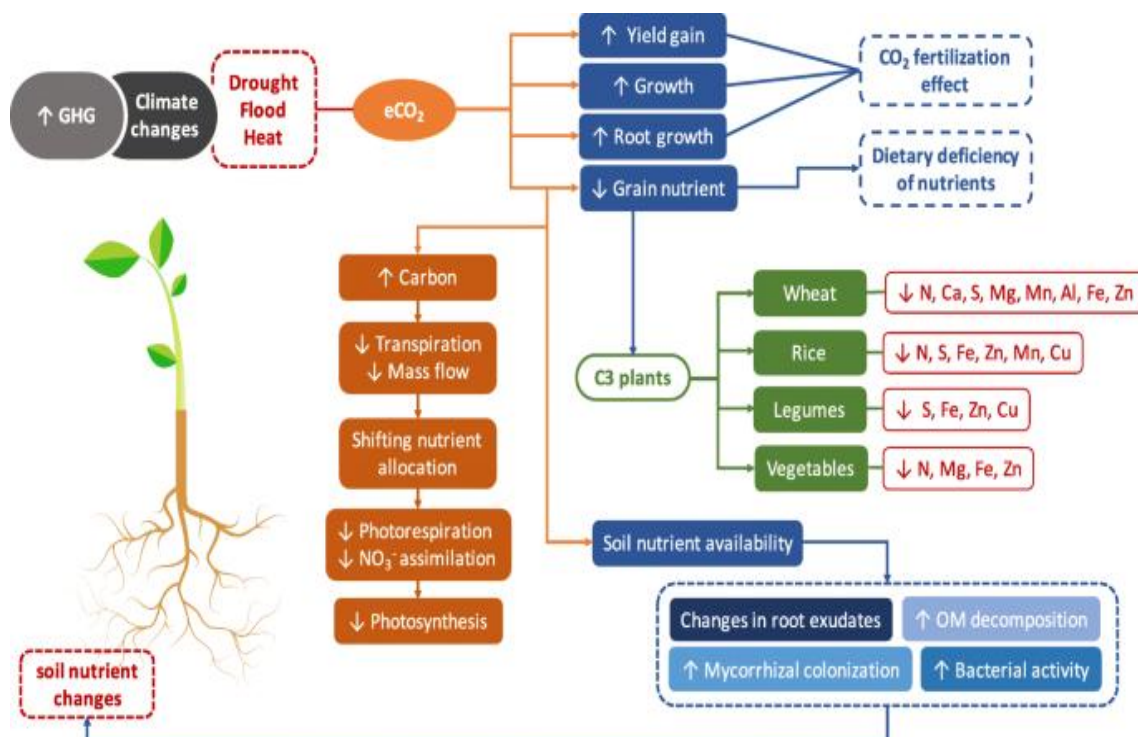


Fig. 11: Schematic illustration of the influence of climatic changes, driven by increased greenhouse gas (GHG) emissions, on grain mineral concentrations and their bioavailability in soil. The effects of CO₂ on nutrient concentrations in edible tissues of C₃ plants are reflected in FACE and non-FACE studies. The mechanisms proposed as responsible for changing the plant mineral concentration are: "carbohydrate dilution" in which there is an increase in carbon (C) assimilation relative to the mineral concentration, decrease in transpiration rates that reduces mass flow of nutrients, and shifting nutrient allocation by altered biochemical processes between tissues can affect nutrient uptake. In addition, down-regulation of photosynthesis and increased photorespiration has been also expected to elucidate the variations in mineral concentrations. The CO₂ concentration has also a direct effect on the bioavailability of nutrients in soils and, consequently, affecting the quantity of existing microorganisms. Possibly, due to changes in soil pH, e CO₂ improves the exudation processes affecting nutrient availability. Furthermore, the role of e CO₂ increasing mycorrhizal colonization and organic matter (OM) decomposition in the soil, facilitating the availability of several nutrients

Carbon dioxide concentration has also a direct effect on the bioavailability of nutrients in soils, and consequently, affecting the number and diversity of existing microorganisms. A positive effect on soil nutrient bioavailability was described under CO₂ enrichment conditions (Jablonski *et al.*, 2002; Kimball *et al.*, 2002). However, the increase in plant growth with eCO₂ may have a disadvantage in terms of competition for micronutrient acquisition with microorganisms prevailing in the soil (Guo *et al.*, 2015). Abbas *et al.*, (2009) showed that eCO₂ promoted increases in P, K, Fe, Mn and Zn in the soil. Possibly, eCO₂ -induced changes in soil pH improves some exudation processes that affects the availability of nutrients in the soil. Similarly, it was described that eCO₂ responses averaged across two N treatments increased the concentrations of Ca, Mg, Fe, Zn and Mn at the soil surface by 15.6, 9.5, 23.4, 138.2 and 16.9%, respectively (Guo *et al.*, 2015; Abou Seeda *et al.*, 2020). In another study, Jin *et al.*, (2019) described the interaction of long-term CO₂ conditions with different soil types (chromosol, vertosol, and calcarosol) on grain nutrient concentrations of wheat, field pea, and canola. At eCO₂, the concentrations of N, P, and Zn decreased by 6, 5, and 10%, respectively, regardless of soil, crop and year. In addition, the concentrations of K, Fe, Mn and Cu were not affected by CO₂ enrichment in any crop grown in the soils tested. Furthermore, e CO₂ may increase mycorrhizal colonization and protect

plants against some stresses, having led to improved P nutrition, particularly on legumes Jakobsen *et al.*, (2016) and increased soil organic carbon decomposition (Abou Seeda *et al.*, 2020). Cheng *et al.*, (2012) facilitating the availability of some nutrients. In sum, a clear understanding of the nutrient-related processes that are impacted by climate change will increase our ability to predict responses for diverse crops and could benefit farmers in agronomic management to adapt crops to higher CO₂. One important final consideration under eCO₂ is the overall effect of lower mineral concentrations while in promoting higher yields. For some situations it has been suggested that regardless of the decrease in grain nutrient concentrations at eCO₂, overall availability of Fe, Zn, Mn, B, Cu, Ca, N, and other macronutrients on a land area basis would actually be enhanced, due to grain yield increase at eCO₂ conditions (Asif *et al.*, 2017a; Fernando *et al.*, 2012b). Elevated atmospheric gradually decreased N, Mg, Fe, and Zn concentrations, and not affected P, K, S, Cu, and Mn concentrations in the edible part of vegetables (Dong *et al.*, 2018b; Abou Seeda *et al.*, 2020). Strong evidence that Zn deficiency is a significant global health problem affecting 17% of the world's population, and that increasing CO₂ levels lower the concentration of Zn in significant food crops (Myers *et al.*, 2017; Myers *et al.*, 2015; Myers *et al.*, 2014). In a meta-analysis with previously published data from FACE and growth chamber experiments, Myers *et al.*, (2014) found a significant reduction in Zn concentration in wheat (-9.1%), rice (-3.1%), barley (-13.6%), field peas (-6.8%), and soybean (-5.0%) grown at eCO₂. Similarly, eCO₂ decreased by 9.4% the Zn concentration in vegetables as described by (Dong *et al.*, 2018b). Thus, due to increased concentrations of atmospheric CO₂ it was anticipated that 138 million of people will be placed at new risk of Zn deficiency by a year of 2050, and the most affected populations live in Africa and South Asia, with a particular incidence in India with 48 million people at risk (Myers *et al.*, 2015). The mechanisms responsible for the overall decline of plant mineral concentrations are not completely deciphered. Despite the “carbohydrate dilution” being a likely cause, it cannot elucidate all the mineral reductions because of the heterogenous response of each mineral tested for a given crop or for different species (Loladze 2002; Poorter *et al.*, 1997). Moreover, decreases in transpiration rates reduces mass flow of nutrients, and shifting nutrient allocation driven by altered biochemical processes between tissues can both change nutrient uptake (McGrath and Lobell, 2013).

However, a trade-off effect must be considered because per serving size, the actual tissues can affect nutrient uptake. In addition, down-regulation of photosynthesis and increased photorespiration have been also expected to elucidate the variations in mineral concentrations. The CO₂ concentration has also a direct effect on the bioavailability of nutrients in soils and, consequently, affecting the quantity of existing microorganisms. Possibly, due to changes in soil pH, eCO₂ improves the exudation processes affecting nutrient availability. Furthermore, the role of eCO₂ increasing mycorrhizal colonization and organic matter (OM) decomposition in the soil, facilitating the availability of several nutrients amount of minerals provided will still be lower, albeit the higher overall grain yields, which may not be sustainable in the long run due to CO₂ acclimatization effects and faster depletion of mineral nutrients from the soil.

4.1. The influence of eCO₂ on protein accumulation

Elevated CO₂ has generally been shown to decrease the concentration of protein in grains of many crops species Dong *et al.*, (2018b); Högy and Fangmeier (2008); Medek *et al.*, (2017); Myers *et al.*, (2017), (2014), directly affecting human nutrition (Toreti *et al.*, 2019). Consequently, millions of people may face protein deficiency since a great part of worldwide population depends on plant proteins (Medek *et al.*, 2017). Medek *et al.*, (2017) confirmed that when grown under eCO₂ conditions expected by the middle of this century (500-700 ppm), a lower protein concentration was found in C3 grains (wheat, rice and barley with -7.8, -7.6, and -14.1%, respectively), potato (-6.4%), vegetables (-17.3%), and fruit (-23.0%). The eCO₂ was also responsible for a slight decrease in protein in legume species (-3.5%), and no significant effects were found in oil crops and C4 plants. Accordingly, they anticipated a decrease in protein intake under eCO₂ conditions by >5% in 18 countries predominantly throughout Middle East and India. Moreover, it was highlighted that almost 12% of the world's population is currently at risk of protein deficiency. In the case of constant atmospheric CO₂, they predict that globally, 15% (1.4 billion people) of world population would be at risk of protein deficiency by 2050 due mainly to demographic changes. However, with projections of CO₂ levels above 500 ppm by 2050, it was expected that an additional 148.4 million people would be at risk of protein deficiency compared to the 2050 aCO₂ scenarios.

Decreasing of micronutrients concentration in food crops will put at risk the populations of the developing world. Iron concentration was also significantly reduced in soybean seeds at fresh edible stage (R6), while Zn and Mn concentrations varied among cultivars Li *et al.*, (2018b). Fig. (12).

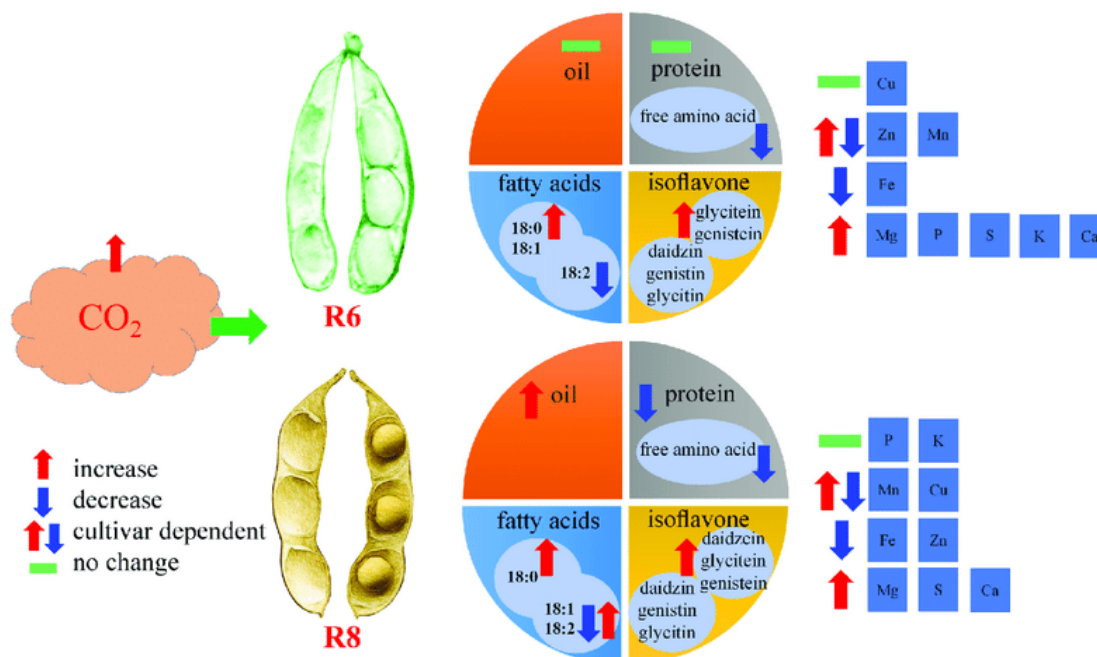


Fig. 12: Diagram illustrating the impact of elevated CO₂ on seed quality of soybean at the fresh edible (R6) and mature stages (R8). After Li, Yansheng *et al.*, (2018)

Li, Yansheng *et al.*, (2018), stated that protein concentration in soybean seeds was significantly decreased under eCO₂; however, oil concentration showed the opposite trend at R8. The free amino acids concentration were significantly decreased under eCO₂, irrespective of the growth stage. Elevated CO₂ resulted in an increase in oleic acid concentration (18:1) of all cultivars at R6. Total isoflavone concentrations were significantly increased at R6 and R8. The concentrations of Fe were significantly decreased at R6 and R8 under eCO₂, while the changes in Zn and Mn concentrations varied among cultivars Fig. (12). These results suggest that eCO₂ may promote fat content by enhancing oleic acid levels (18:1) but decrease the content of proteins and relevant amino acids.

4.2. Modification of root architecture, and its important

Root architecture modification and down regulation of photosynthesis. Taub and Wang (2008), and also inhibition of nitrate assimilation by decreased photorespiration Bloom *et al.*, (2002) have been proposed to elucidate the variations in mineral concentrations. The CO₂ concentration has also a direct effect on the bioavailability of nutrients in soils, and consequently affecting the number and diversity of existing microorganisms. A positive effect on soil nutrient bioavailability was described under CO₂ enrichment conditions (Jablonski *et al.*, 2002; Kimball *et al.*, 2002). However, the increase in plant growth with eCO₂ may have a disadvantage in terms of competition for micronutrient acquisition with microorganisms prevailing in the soil (Guo *et al.*, 2015). Abbas *et al.*, (2009) showed that eCO₂ promoted increases in P, K, Fe, Mn and Zn in the soil. Possibly, eCO₂-induced changes in soil pH improves some exudation processes that affect the availability of nutrients in the soil. Similarly, it was described that eCO₂ responses averaged across two N treatments increased the concentrations of Ca, Mg, Fe, Zn and Mn at the soil surface by 15.6, 9.5, 23.4, 138.2 and 16.9%, respectively (Guo *et al.*, 2015). In another study, Jin *et al.*, (2019) described the interaction of long-term CO₂ conditions with different soil types (Verti and calcareous soils) on grain nutrient concentrations of wheat, field pea, and canola. At eCO₂, the concentrations of N, P, and Zn decreased by 6, 5, and 10%, respectively, regardless of soil, crop and year. In addition, the concentrations of K, Fe, Mn and Cu were not affected by CO₂ enrichment in any crop grown in the soils tested.

The effects of elevated atmospheric CO₂ concentration on soil microbial community structure are often characterized by an increased mycorrhizal colonization due to the increased plant demand for nutrients, coupled with increased C assimilation rates. CO₂ enrichment should increase mycorrhizal biomass because plant demands for N and P will increase concurrently with C assimilation rates, and plants will allocate more photosynthates belowground to the roots and mycorrhizal fungi to help satisfy this increased nutrient demand. Greater fine root mass and mycorrhizal infection promote enhanced P uptake in mycorrhizal plants grown under elevated CO₂ concentrations. It seems reasonable to expect that at elevated CO₂ levels, mycorrhizal biomass will increase as C becomes relatively less limiting and soil nutrients become more limiting to plant growth (Drigo *et al.*, 2008).

The response of soil microorganisms to changes in plant production under elevated CO₂ is highly variable due to very different patterns of plant C allocation in different plant–soil systems. Microbial biomass, gross N mineralization, microbial immobilization, and net N mineralization under elevated CO₂ show a high degree of variability. However, rates of soil and microbial respiration are generally more rapid under elevated CO₂, indicating that enhanced plant growth under elevated CO₂ increases the amount of C entering the soil, thereby stimulating soil microbial activity. Soil microorganisms are often C-limited and therefore, increased C availability stimulates microbial growth and activity. It is generally assumed that the CO₂ induced increases in soil C availability will increase fungal biomass more than bacterial biomass. It is because of increased concentrations of dissolved organic C in the rhizosphere and to increases in soil water dissolved organic N. Given the important roles played by fungi in organic matter degradation, nutrient cycling, plant nutrition, and soil aggregate formation, shifts in fungal communities might have a strong impact on soil functioning. Furthermore, lower N availability at elevated CO₂ may, in part, explain these increases in fungi, as fungi tend to have a higher C/N ratio than bacteria and so have a lower demand for nitrogen than bacteria have. Hu *et al.*, (2001) Bacteria and fungi, the initial consumers of soil organic matter, are themselves substrates for a multitude of tiny predators and grazers, including protozoa, nematodes, and arthropods, which comprise the soil food web. Therefore, an increase in bacterial growth due to an increasing C allocation at elevated atmospheric CO₂ levels may be followed by an increase in grazing, resulting in a higher turnover of the microbial biomass. Increased grazing thus, results in faster recycling of nutrients from the microbial biomass, which would increase the flux of nutrients to the plant. Furthermore, eCO₂ may increase mycorrhizal colonization and protect plants against some stresses, having led to improved P nutrition, particularly on legumes Jakobsen *et al.*, (2016) and increased soil organic carbon decomposition Cheng *et al.*, (2012) facilitating the availability of some nutrients. Climate change will increase our ability to predict responses for diverse crops and could benefit farmers in agronomic management to adapt crops to higher CO₂. Decreasing CO₂ gradually stimulated the concentration micronutrients and furthermore promoting higher yields. For some situations it has been suggested that regardless of the decrease in grain nutrient concentrations at eCO₂, overall availability of Fe, Zn, Mn, B, Cu, Ca, N, and other macronutrients on a land area basis would actually be enhanced, due to grain yield increase at eCO₂ conditions (Asif *et al.*, 2017a; Fernando *et al.*, 2012b).

Micronutrients play a decisive role in maintaining health, because they have an essential role in cognitive growth and development Abou Seeda *et al.*, (2020), in reproductive functions and cell metabolism, and in immune system responses of humans (Nakandalage and Seneweera, 2018). Limitation of Fe adversely disturbs growth, immune function and is the most common and widespread nutritional disorder in the world causing anemia (Murgia *et al.*, 2012; Abou Seeda *et al.*, 2020). Current studies show that Fe deficit in the first year of life is responsible for permanent effects on brain development, structure and function (Beard, 2008). Furthermore, 0,2% of deaths in children under 5 years of age can be attributed to Fe deficiency (Murgia *et al.*, 2012).

Various biological functions have been attributed to Zn, since it cooperates with many enzymes and other proteins and performs critical structural, functional and regulatory roles in the body (Krężel and Maret 2016; Abou Seeda *et al.*, 2020). A large consumption of cereal-based foods is considered the main driver to Zn deficiency, since cereals have low concentration and bioavailability of Zn and cannot meet the human demand for Zn (Cakmak and Kutman, 2018). Nowadays, wheat, rice and corn account for about 60% of the world's daily energy consumption, and bread wheat alone is the staple food for about 35% of the world's population (Poursarebani *et al.*, 2014). Countries with a high incidence of Zn and Fe-deficiencies, rice and wheat deliver over 70% of the daily calorie intake in rural areas (Cakmak *et al.*, 2010; Cakmak and Kutman, 2018). The goal of biofortification is to solve some of these problems

by increasing the concentration of micronutrients in the edible parts of crops that improving their bioavailability and absorption in the human body after digestion (Carvalho and Vasconcelos 2013; Thornton, *et al.*, 2014; Vasconcelos *et al.*, 2017; Bouis and Saltzman, 2017). Plants require 14 mineral nutrients to achieve for optimal development and growth (Marschner, 2012; Abou Seeda *et al.*, 2020). These elements are structural components of numerous macromolecules including nucleic acids, phospholipids, certain amino acids, and several coenzymes and play a central role in plant cellular metabolism (Grusak, 2001). In addition, they are beneficial in chlorophyll biosynthesis, redox reactions, plasma membrane integrity and contribute to the osmotic potential of cells (Nakandalage and Seneweera, 2018). Micronutrient insufficiencies affect plant growth and yield by limiting the biosynthesis or expression of important mechanisms of energy capture and/or metabolism (Grusak, 2001). Therefore, an increase in the vulnerability to abiotic stresses is usually encountered in plants that experienced micronutrient deficiency (Bencke-Malato *et al.*, 2019; Hajiboland, 2012; Jin *et al.*, 2009).

5. Factors Affecting Mobility and Bioavailability of Phosphorous

5.1. Plant phosphorous requests extending CO₂ elevated

Phosphorus is a unique nutrient among the essential plant nutrients with respect to increasing atmospheric CO₂ concentrations. It plays an essential role in plant metabolism as it is involved in conserving and transferring energy in cell metabolism Raghothama, (1999); Abel *et al.*, (2002); Lambers *et al.*, (2006), Abou Seeda *et al.*, (2020), and is an indispensable structural component of nucleic acids, coenzymes, nucleotides, phosphoproteins, phospholipids and sugar phosphates (Schachtman *et al.*, 1998; Veneklaas *et al.*, 2012). The growth increases from elevated CO₂ are likely to require more P, which is taken up from the available P pool in soil (Edwards *et al.*, 2005; Gentile *et al.*, 2012; Jin *et al.*, 2012). Several studies have reported that both the magnitude and the direction of the growth response of plants to elevated CO₂ depend on P availability (Bassiri Rad *et al.*, 2001; Jin *et al.*, 2013). However, only a small proportion of total soil P in generally.

These strategies facilitate the mobilization of P from these non-labile pools, and thereby P availability has been enhanced over a large time scale in weathered soils with the evolution of these strategies (Lambers *et al.*, 2008; Abou Seeda *et al.*, 2020). These evolved strategies induce feedback processes between plants and soils, which are relevant to the photosynthetically fixed C and its allocation (Buendía *et al.*, 2014). Increased C fixation and more belowground investments promote P-enhancing processes in the soil (De Lucia *et al.*, 1997; Allen *et al.*, 2003). Thus, an important consideration here is that elevated CO₂ will generally increase the C allocations to roots and the increase in root C will stimulate root growth (Rogers *et al.*, 1992 1994; Li *et al.*, 2012) and increase exudate secretions from the roots. This, in turn, will influence conditions in the rhizosphere, which is the interface between plant roots and soil (Paterson *et al.*, 1997; Haase *et al.*, 2008; Drigo *et al.*, 2013). The changes in rhizosphere environment are likely to affect P acquisition by plants. Questions therefore arise as to whether plant P demand on the one hand and P acquisition on the other will be affected more by the increase of atmospheric CO₂ concentrations. Understanding this supply–demand balance for labile soil P will be important for developing P management strategies in agricultural systems to cope with increasing atmospheric CO₂ concentrations. Elevated CO₂ is likely to affect the internal P requirement of plants because elevated CO₂ alters P utilization within plant tissues (Niu *et al.*, 2013a).

5.2. Their impact on plant strategies to achieve phosphorous

Current crop production in P-deficient soils is heavily reliant on the application of P fertilizers. However, more intensive fertilization with phosphorous is likely to become problematic in the long term, to provide for the increasing P demands of crops under elevated CO₂, because reserves of phosphate ore deposits are finite (Lynch, 2011). There are also concerns about the environmental impact resulting from intensive P fertilization. Thus, it is increasingly important to improve plant P acquisition and P-use efficiency under elevated CO₂. Elevated CO₂ is likely to affect the P acquisition strategies in several ways. The increase in C assimilation in plants grown under elevated CO₂ is likely to lead to a considerable response in root growth, including changes in root architecture and morphology that will affect P acquisition from soil profiles. Second, the composition and quantity of root exudates are likely to alter under elevated CO₂ and hence these will change rhizosphere properties such as pH, Eh and the capacity for chelation and ligand exchange, which in turn will affect P availability. Third, these root exudates may also modify the association between microorganisms and P transformations.

5.3. Rhizosphere activities in response to elevated CO₂ and phosphorous availability

The effect of elevated CO₂ on rhizosphere properties is likely to impact on the ability of plants to acquire P from the soil. Elevated CO₂ is likely to increase C flow from plant to soil by increasing the release of root exudates (Lin *et al.*, 2000; Song *et al.*, 2014). These exudates contain functional molecules that facilitate an increase in rhizosphere P solubility, and hence improve P nutrition to plants (Richardson *et al.*, 2009; Abou Seeda *et al.*, 2020). Furthermore, root exudates are responsible for changes of rhizosphere pH and increases in microbial activity (Shen *et al.*, 2011). These effects of elevated CO₂ can change P availability in the rhizosphere and consequently influence plant P acquisition (Norby *et al.*, 2001; de Graaff *et al.*, 2006).

5.4. Root exudates

Exudates released from roots into the rhizosphere can affect the availability of soil P to plants (Randall *et al.*, 2001; Betencourt *et al.*, 2012). Low-molecular-weight carboxylates present in root exudates have been considered to be Pi-mobilizing agents (The effectiveness of these carboxylates to mobilize P depends largely on carboxyl (-COOH) and hydroxyl (-OH) functional groups in these molecules. Citrate (tricarboxylic acid, TCA) exhibits the greatest ability to desorb P, followed by oxalate (dicarboxylic acid), while malate, malonate and tartarated are moderately effective (Abou Seeda *et al.*, 2020; Bolan *et al.*, 1994; Jones, 1998; Jones *et al.*, 2009; Richardson *et al.*, 2009). Citrate is particularly effective at mobilizing P from Fe-phosphates and Al-phosphates in acid soils Bolan *et al.*, (1994) and Ca-phosphates in calcareous soils, or from rock phosphate fertilizer (Dinkelaker *et al.*, 1989). The mechanism by which the carboxylates in root exudates affect soil P mobilization under elevated CO₂ is not known. Shen *et al.*, (2011) suggested that desorbing and chelating P from Al-P and Fe-P complexes and from other non-labile pools mobilizes P. However, the extent that elevated CO₂ increases P desorption depends on whether elevated CO₂ stimulates the release of those carboxylates that are effective in mobilizing Pi. Significant volumes of root exudates have been measured following elevated CO₂ exposure (van Ginkel *et al.*, 2000; Allard *et al.*, 2006). For example, after 34 weeks of growth under elevated CO₂, the exudation of soluble C compounds from roots of short-leaf pine increased by 50 % (Norby *et al.*, 1987). Similarly, the release of low molecular-weight organic compounds increased by 120–160 % and amino acids increased by 250 % when *Pinus sylvestris* was grown for 5 weeks in a nutrient solution under elevated CO₂ (700 ml L⁻¹) in comparison with ambient CO₂ (350 ml L⁻¹) Johansson *et al.*, (2009). Haase *et al.*, (2007) also found that the release of malate, which is the major organic acid in the exudates from *Phaseolus vulgaris*, increased by 177 % after the plants were exposed to elevated CO₂ (800 ml L⁻¹) for 18 d. The increase of these organic compounds is likely to mobilize P in the rhizosphere but to date the mobilization.

5.5. Acidity of soil rhizosphere

Soil pH can greatly influence the solubility of P in soils (Shen *et al.*, 2011). In acid soils where the concentrations of trivalent Fe and Al are high, labile Pi in soil solution is easily precipitated as Fe- and Al-phosphates or sorbed onto Fe- and Al-(hydr) oxides (Abou Seeda *et al.*, 2020). In contrast, in alkaline soils where Ca is the major cation, Pi is predominantly precipitated as Ca-phosphates (Richardson *et al.*, 2009). Thus, soil pH from 6.0 to 7.0 provides optimal conditions for P solubility (Hinsinger, 2001). Given this relationship between soil pH and P availability, any process that alters soil pH will influence P availability in the soil solution. There are several ways that elevated CO₂ is able to change P availability by modifying the rhizosphere pH. The first is that elevated CO₂ may change the quantity of organic acid anions and associated protons released in exudates from plant roots, leading to pH changes in the rhizosphere (Guo *et al.*, 2012). Organic acid anions have often been associated with the release of protons as a source of rhizosphere acidification (Hoffland *et al.*, 1989; Hinsinger *et al.*, 2003). For example, the release of citrate from cluster roots of white lupin was associated with strong rhizosphere acidification (Neumann and Römheld, 1999), which suggests that H⁺ ions released to accompany the efflux of citrate were a major component of the observed acidification of the rhizosphere. As elevated CO₂ is likely to increase the exudation of organic acid anions, the H⁺ extrusion accompanying this exudation would lower pH and thereby enhance P mobilization in alkaline soils rather than acidic soils (Bayuelo-Jiménez and Ochoa-Cadavid, 2014). The second way that elevated CO₂ might affect rhizosphere pH results from the large amount of CO₂ derived from the respiration of the root and the microbes in the rhizosphere under elevated CO₂. The increased activities of rhizosphere

microorganisms Jin *et al.*, (2014) under elevated CO₂ are likely to increase CO₂ concentration in soil Matamala and Schlesinger, (2000); Carrillo *et al.*, (2014) and this CO₂ will dissolve in soil H₂O to form H₂CO₃. As a result, the pH in the rhizosphere is likely to decrease. However, this scenario in terms of rhizospheric pH may be marginal, because gaseous CO₂ diffuses much faster than H₂CO₃ in solution Anoua *et al.*, (1997); Hinsinger *et al.*, (2003), and only neutral to alkaline soils can respond to the change in soil CO₂ concentrations because H₂CO₃ with its first pK of 6.36 remains undissociated at low pH Lindsay, (1979).

6. Root Network Mechanisms, and Their Importance

Phosphorous is an immobile nutrient in soil, increases in root length and root branching under elevated CO₂ may increase the plant's capacity to acquire P from the soil. The effect of a larger root system is shown by the work of Hammond *et al.*, (2009) Fig. (13). They stated that P uptake in *Oryza sativa* and *Brassica oleracea* genotypes under low P supply was correlated with lateral root growth rate, lateral root length, the number of lateral roots and root surface area.

Ajmera *et al.*, (2019) reported that Phosphate starvation responses (PSRs) act at different temporal and spatio-physical scales, i.e., field, rhizosphere, plant, organ, tissue, cell and sub-cell, Fig. (14). Plants integrate intrinsic and extrinsic factors, eliciting such responses to counter phosphate stress. This relies on both local and systemic sensing/signaling mechanisms that monitor external and internal phosphate status. External Pi is sensed by a local system around the root-tip Svistoonoff, *et al.*, (2007), particularly, in the root cap (Bonnot, *et al.*, 2016). This independently attenuates primary-root growth and promotes root-hair development in *Arabidopsis* (Chiou, *et al.*, 2011). Along with genetic regulation, modulation in the dynamics of different hormones plays an important role in such local responses, leading to altered RSA,

In addition, the root hairs also contributed to P acquisition with direct evidence coming from studies with mutant plants with no root hairs (Bates and Lynch, 2000), and from the comparison of species and genotypes that have contrasting length and density of root hairs (Richardson *et al.*, 2011). Some changes in root morphology that develop in response to P deficiency are important for P acquisition efficiency by plants (Lambers *et al.*, 2006; Pang *et al.*, 2010). Root morphology will probably change in response to elevated CO₂ and this will alter the P-acquisition efficiency. The increase in photosynthetic C allocation to roots under elevated CO₂ results in stimulation of root growth more than the growth of other plant organs (Norby *et al.*, 1992; Benlloch-Gonzalez *et al.*, 2014). The elevated CO₂-mediated increase in root growth will bring about increases in root length, number, diameter and branching. Yang *et al.*, (2007) showed that compared with ambient CO₂ (350 µl L⁻¹), 550 µl L⁻¹ increased root biomass by 45 %, root volume by 44 %, number of adventitious roots by 31 % and overall root length by 37 % when rice plants were grown in a Stagnic Anthrosol soil. A greater number of root clusters and a higher percentage of lateral roots were also observed in white lupin (*Lupinus albus*) grown under elevated CO₂ (Watt and Evans, 1999; Campbell and Sage, 2002).Fig. (14).

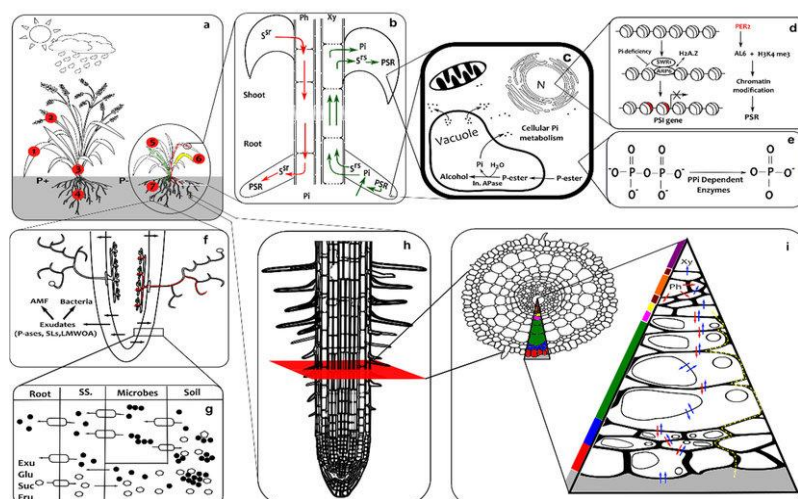


Fig. 13: Illustrates the integrated overview of phosphate starvation responses. The responses and signalling mechanisms operate at a range of scales and different locations which are depicted in nine connected panels: (a) denotes the whole plant and field scale; the numbers in red circles represent normal and low inorganic phosphate conditions (1) phosphorus playing a major role in various plant growth and developmental process including photosynthesis; (2) the highest level of Pi being found in the vegetative parts of the young plant, which upon maturation, moves into (3) fruit and seeds; (4) root development correlating with Pi levels; (5) Pi helping to increase water use efficiency and disease resistance; (6) abnormal leaf dis colouration under low Pi conditions; and (7) shallow root system with more root hairs and lateral roots. (b) denotes the whole plant scale with systemic signals systemic shoot to root (SSR) from shoot through the phloem to the root and systemic root to shoot (SRS) from the root to the shoot through the xylem; Pi, and water and other nutrients also go up to the shoot by this route. (c) Denotes cells from any part of the plant which responds to phosphate deprivation altering the lipid content, releasing phosphate stores from the vacuole where Pi is liberated from esters by Acid Phosphatases (APase). (d) denotes the epigenetic effects (principally chromatin modification) that influence transcription of Phosphate Starvation Response genes. (e) Denotes the pyrophosphate-dependent glycolytic bypass enzymes and metabolic Pi recycling system. (f) denotes rhizosphere activities, specifically the exudation of acid phosphatases (P-ases), Strigalactones (SLs) and Low Molecular Weight Organic Acids (LMWOA) which stimulate bacterial activity and attract Arbuscular Mycorrhizal Fungi (AMF) that form arbuscular structures within the root – mycorrhizal delivery of Pi is depicted in red. (g) denotes a close-up view of the rhizosphere boundaries between the root, soil sheath (SS), microbes and soil where exudates and sugars (Glu), glucose, (Suc), sucrose and (Fru), fructose, are secreted through efflux transporters respectively to solubilize Pi compounds and stimulate bacteria to do the same, and Pi is imported through transporters of varying affinity; the exudates/sugars, transporters and Pi are respectively depicted by hollow ellipses, lozenges with directional arrows and black circles. (h) denotes the alteration in meristem and elongation zone length and the formation of root hairs. (i) denotes a cross section through a root and the paths taken during Pi uptake: the positions of different tissues within a root, namely, epidermis, exodermis, sclerenchyma plus cortex, endodermis, pericycle, phloem, cambium and xylem are marked respectively by red, blue, green, pink, yellow, orange, pale brown and purple; and transport of shoot-to-root signal molecules, symplastic/inter-organellar Pi and apoplastic Pi are depicted respectively by red, blue and dashed yellow arrows.

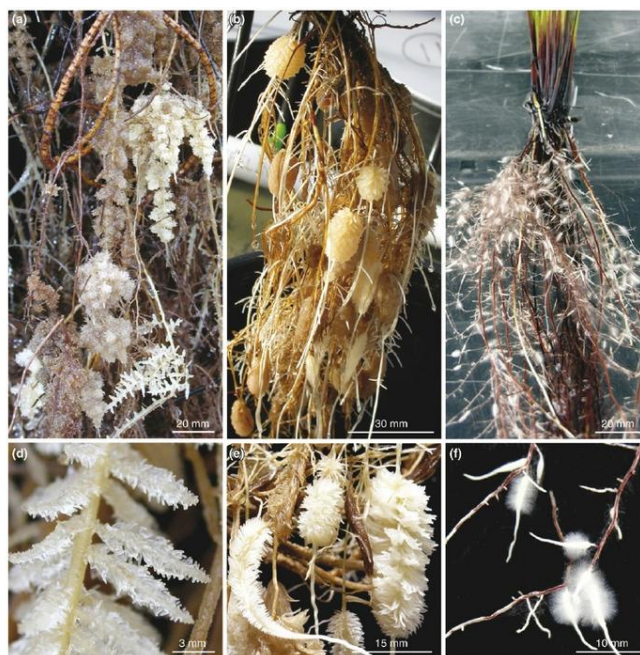
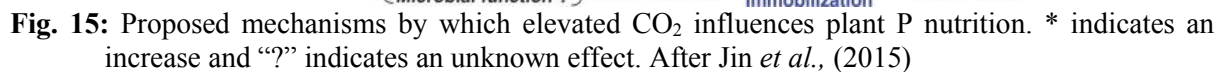


Fig. 14: Represents root morphology of Australian *Proteaceae* and South African *Cyperaceae* species grown hydroponically at extremely low P supply (1 mM). (a) *Dryandra sessilis* (*Proteaceae*) root system with ‘compound’ ‘proteoid’ root clusters. (b) *Hakea prostrata* (*Proteaceae*) root system with ‘simple’ ‘proteoid’ root clusters. (c) *Tetraria* species (*Cyperaceae*) root system with ‘dauciform’ root clusters. (d) Compound proteoid root cluster of *Banksia grandis* (*Proteaceae*, Western Australia) terminate with third-order branch rootlets. (e) Simple proteoid root cluster of *Hakea sericea* (*Proteaceae*, eastern Australia) terminate with second-order branch rootlets. (f) Root hairs at very high density on individual dauciform root clusters (higher magnification of *Tetraria* species in photograph (c) above). Photographic plate courtesy Michael W. Shane (School of Plant Biology, the University of Western Australia).

Similar trends were found in chickpea, soybean, field pea, wheat, sorghum and cotton (Del Castillo *et al.*, 1989; Rogers *et al.*, 1992, 1994; Jin *et al.*, 2013, 2015). These changes in root morphology result in an increase in the spread of roots through the root zone, which should lead to increases in nutrients uptake (Baker *et al.*, 1990; Idso and Kimball, 1991, 1992; Rogers *et al.*, 1992) Abou Seeda *et al.*, (2020).

Jin *et al.*, (2012), who reported a significant positive relationship between root length and P uptake under both ambient CO₂ and elevated CO₂, found a similar result. The longer roots under elevated CO₂ in that study resulted in greater P acquisition. Thus, it appears that root growth positively responds to elevated CO₂, enabling the roots to explore a larger volume of soil, and this will increase the plant’s ability to take up nutrients (Nie *et al.*, 2013), especially, immobile phosphate ions. The response of root morphology to elevated CO₂ and the impact on P acquisition are fundamentally regulated at the genetic level. Ainsworth *et al.*, (2006) reported that there were 327 independent genes that were CO₂-responsive when soybean plants were exposed to elevated CO₂, while Raghothama (1999) reported that there were more than 100 genes involved in plant response to P deficiency. Auxin genes including auxin-responsive promoters Chandler, (2009) and auxin transport genes (Santelia *et al.*, 2005) are thought to be the most responsive genes to elevated CO₂ and external P status. Auxins are hormonal compounds that regulate plant growth processes, such as the initiation and elongation of root hairs (Pitts *et al.*, (1998); Schiefelbein, (2000). Niu *et al.*, (2011), found that elevated CO₂ resulted in the expression of auxin-specific genes, which were likely to enhance the growth of root hairs in *Arabidopsis*, Fig. (15).



Further investigation of these genetic factors that mediate root development will be required to reveal the molecular mechanisms by which the plant adapts to P deficiency as well as elevated CO₂ environments Fig. (17).

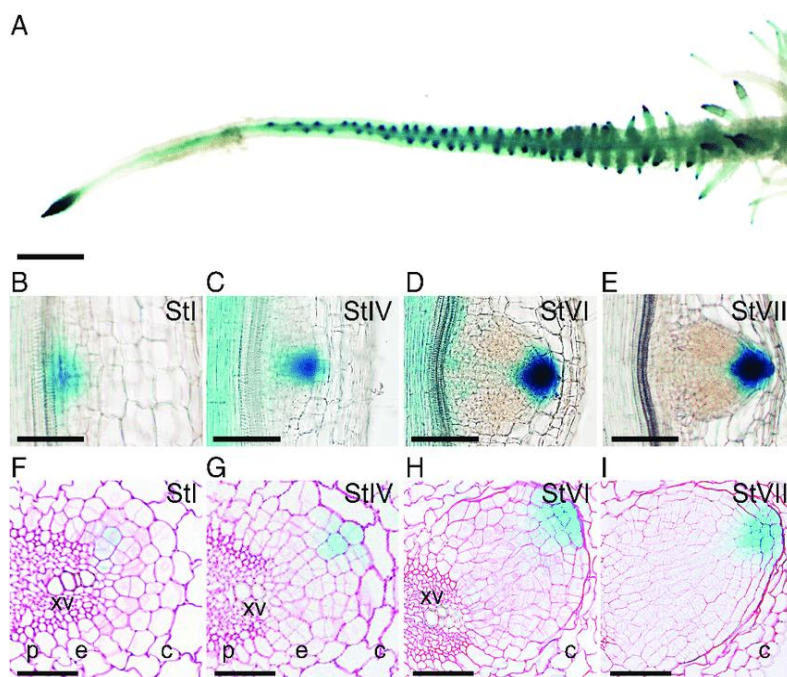


Fig. 17: Establishment of an auxin gradient during CR and rootlet development. (A–I) *DR5: GUS* pattern of expression in lupin ‘hairy root’ seedlings grown on low-phosphate medium. (A) Fully mature whole CR. (B–E) *DR5: GUS* expression was observed on thick longitudinal sections (80 μm) at stage I (B), stage IV (C), stage VI (D) and stage VII (E). (F–I) *DR5: GUS* expression was also observed on thin cross sections (6 μm) in the juvenile region of the CR counterstained with ruthenium red at corresponding stages: stage I (F), stage IV (G), stage VI (H) and stage VII (I). P, pericycle; e, endodermis; c, cortex; xv, xylem vessels. Scale bars are 100 μm. After Gallardo *et al.*, (2019)

Gallardo *et al.*, (2019) reported that during rootlet morphogenesis. Auxin play a major role for development describing in detail by Lavenus *et al.*, (2013), notably with the help of the synthetic auxin reporter R5 (Ulmasov *et al.*, 1997). We generated white lupin composite transgenic ‘hairy root’ plants expressing the *DR5* reporter fused to the *B*-glucuronidase gene. Our first goal was to determine whether the ‘hairy root’ system is suitable to observe auxin-related developmental mechanisms and subsequently to determine whether an auxin gradient is established during rootlet organogenesis. In white lupin, the *DR5* marker, an artificial promoter made of seven tandem repeats of an auxin responsive element isolated from soybean (*Glycine max*), showed that a strong conserved pattern as compared to other species. *DR5* expression was seen in the CR tip and vasculature Fig. (17). In rootlet primordium, GUS activity was observed at stage I of development Fig. (17), in one of the first dividing cells, close to the protoxylem pole. At stage IV, when divisions give rise to a dome-shaped primordium, GUS activity was observed in a few cells at its tip Fig. (17). From this stage onwards, a strong *DR5* response builds up in the primordium apex Fig. (17). After emergence, strong GUS activity was detected in the root cap whereas the zone above the rootlet tip was displaying a weak GUS activity Fig. (17). Expression in the vasculature was observed in mature rootlets Fig. (17). Our observations of the *DR5: GUS* reporter suggest that an auxin gradient is established during rootlet initiation up to their emergence and maintained during their later development.

Specifically, the quantitative relationship between auxins and pericycle cell division leading to the development of new roots, and the elevated CO₂/P supply responsive molecular pathways that regulate the expression of auxin-responsive genes warrant future. The low availability of Pi is attributed its uneven distribution and immobility in soil Phosphate (Pi) availability has a strong effect on root system architecture (RSA), which shows distinct difference with those caused by the deficiency of other

nutrient ions, such as nitrate Zhang *et al.*, (1999) and iron Moog *et al.*, (1995). Under P deficiency, plants are commonly characterized by the change of root morphology and better proliferation of roots relative shoots (Holford (1997), Hinsinger (2001) Lynch and Brown (2008).

Root architecture, and its adaptation is actually important for nutrients absorption particularly for phosphorous which is less mobile element Lynch (2007); Zhu *et al.*, (2005). Architectural adaptations are related to the change in root branching, root length, and formation of root hairs López-Bucio *et al.*, (2002); Richardson and Simpson (2011); Trachsel *et al.*, (2011) Fig. (18).

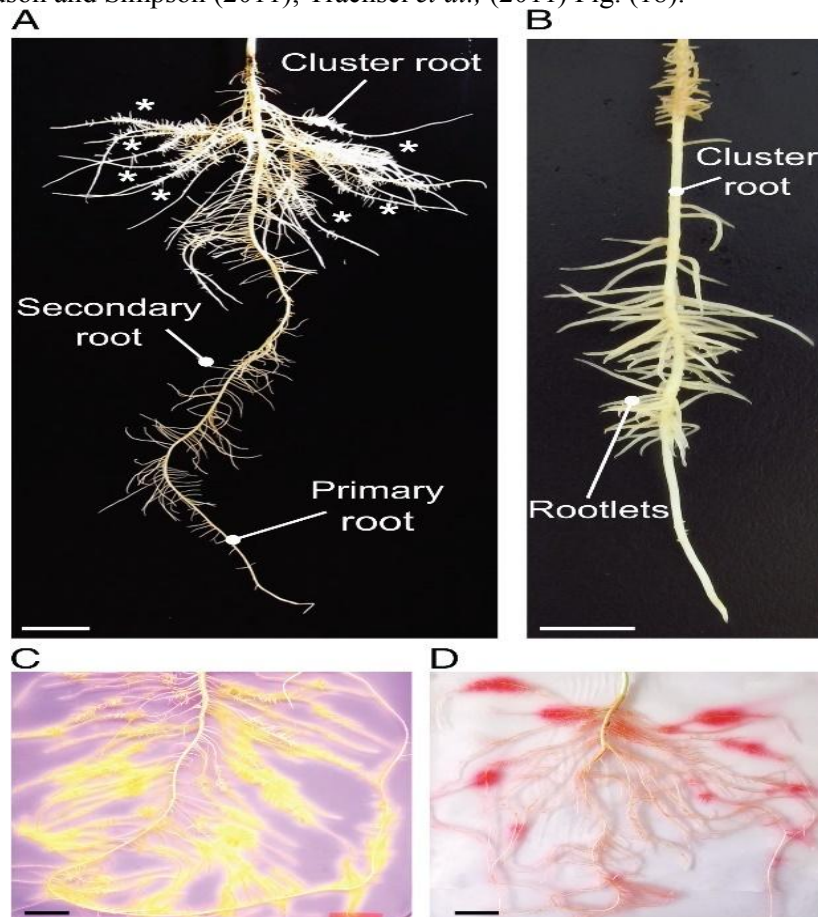


Fig. 18: White lupin architecture and physiology in low phosphate conditions. (A and B) Root architecture of a 21-day-old white lupin (*Lupinus albus*) comprising many CRs in the upper part of the root system (asterisks). CRs are secondary roots producing hundreds of short roots with determinate development, known as rootlets (B). (C and D) Physiological assays of 19-day-old lupin root systems placed on agar plates containing bromocresol purple (BCP) (C) or bathophenanthroline disulfonic acid disodium salt (BPDS) in the presence of Na-Fe EDTA (D). (C) BCP is a purple pH indicator that turns yellow when the roots are acidifying the medium with proton excretion (pH), After Gallardo *et al.*, (2019)

Gallardo *et al.*, (2019) Abou Seeda *et al.*, (2020), reported that lateral roots (LRs) producing bottlebrush-like clusters of short rootlets as presented in Fig. (18), these organs represent an evolutionary adaptation to phosphorus-impoverished soils. As a result, CRs exhibit four main characteristics regarding their development and physiology Skene (2000): (1) a massive induction of rootlets (up to 20–100 per cm); (2) a determinate development leading to a limited growth and subsequent entry into senescence; (3) an exudative burst resulting in massive secretion of protons, organic acids, phenolics and phosphate remobilizing enzymes and (4) a high phosphate uptake capacity. The secretion of protons can be imaged with a pH indicator such as bromocresol purple (Fig. 18C). A high level of ferric reductase activity is also associated with CR physiology and can be revealed biochemically (Fig. 18D). White lupin (*Lupinus albus*) is an annual legume traditionally cultivated around the Mediterranean and is the only cultivated crop that can form CRs. It is a model of interest because of its quick life cycle compared to other species, mainly bushes and trees, sharing the ability to

form these structures. Moreover, white lupin has the capacity to form nitrogen-fixing nodules because of the symbiotic interaction with *Bradyrhizobium sp.* but has lost the ability to form mycorrhizal associations (Lambers and Teste, 2013). Interestingly, many CR forming species share this lack of ability for mycorrhization. The capacity to form CRs in lupin allows a reduction of phosphate fertilizer use in the field and results in a beneficial interaction in mixed cultures Cu *et al.*, (2005); this represents an interesting example to lower our dependency on this source of agricultural input.

Plants differ in the mechanisms for absorption of P from deficient environments. Efficient plant genotypes may have adaptations to explore more soil by increasing surface area, transforming plant-unavailable forms of nutrients in available forms, and take up nutrients across the plasma membrane (Khurshid *et al.*, 2017). Plant roots perform a range of functions in plants like anchorage and absorption of nutrients and water (Bertin *et al.*, 2003; Lambers *et al.*, 2006, 2010; López-Bucio *et al.*, 2003). Thus, the changes in the root architecture could affect nutrient and water absorption by plants. Root architecture is affected by three major processes, viz., (1) cell division at the primary root meristem, which determines growth by adding new cells to the root, (2) lateral root formation that improves exploration of soil by the roots, and (3) development of root hairs, thereby increasing the root surface area (López-Bucio *et al.*, 2003). The rooting pattern of plants is mainly determined by the plant species, soil structure, and their interaction (Kim, *et al.*, 2018). The larger root system provides more surface area for nutrient absorption by increasing the contact with soil which plays an important role for P absorption (Ou *et al.*, 2018; Gahoonia and Nielsen 1998; Lynch, 2007; Römer and Schenk, 1998). Distribution of nutrients in soils is heterogeneous or patchy. In order to enhance nutrient uptake, plant roots have to exploit these nutrient patches. Asymmetrical development and exceptional flexibility in architectural patterns of roots enable plants to exploit soils and allow root proliferation in nutrient-rich zones (Lynch, 1995). Depending upon the plant species and environmental conditions, the root systems vary widely in terms of root architecture, including number and size of root hairs (Lambers and Shane 2007; Lynch and Brown 2001; Shane *et al.*, 2006). Various root characteristics including root architecture, root diameter, root hairs, cluster roots Bates and Lynch (2000); Hill *et al.*, (2006); Singh Gahoonia and Nielsen (2004), symbiotic relationship with mycorrhiza, kinetics of P uptake, and rhizospheric processes Aziz *et al.*, (2011a), Hinsinger (2001); Pang *et al.*, (2010); Ryan *et al.*, (2009) cause variations in P uptake among the plant species/cultivars (Lynch and Brown 2001; Singh Gahoonia and Nielsen, 2004). Response to P deficiency by plant roots involves changes in root architecture and the shift of biomass allocation from basal to adventitious roots in such a way to explore more topsoil or P-rich Lambers and Shane (2007) sites for P acquisition Liao *et al.*, (2001), (2004); Lynch and Brown (2001). These adaptations include horizontal basal root growth, increased adventitious root formation, enhanced lateral root formation, and increased root hair density and length (Bonser *et al.*, 1996; Liao *et al.*, 2001; Lynch, 2007). Topsoil foraging is strongly associated with P acquisition in low-P soils Rubio *et al.*, (2003); Zhu *et al.*, (2005) due to low mobility of P in soil. Low P in the rooting zone favors the formation of lateral roots (López Bucio *et al.*, (2002); Lynch (2007). A large root surface area is achieved by a combination of reduced mean root diameter and elongation of relatively thinner roots (Fitter *et al.*, 2002). Root diameter is very important in exploration of soil volume by roots as it determines the volume of soil that can be explored by the roots (Fitter, 1991; Gahoonia *et al.*, 2006). Plants with a smaller root diameter can explore more soil per unit of root surface area Fitter *et al.*, (1991) and can efficiently uptake P from limiting environments (Singh Gahoonia and Nielsen, 2004). Root hair enhances the ability of roots to explore the rhizosphere for P due to increased surface area for absorption (Hill *et al.*, 2010; Ma *et al.*, 2001b; Zhu *et al.*, 2010). Root hairs constitute up to 77 % of the total root surface area and thus are the major point of contact between plants and the rhizosphere (Föhse *et al.*, 1991; Gahoonia and Nielsen, 1998). Under P deficiency, increased root hair density and length is well documented in legumes Yan *et al.*, (2004) and barley Gahoonia and Nielsen (1998). Ma *et al.*, (2001a) reported that root hair density in *Arabidopsis thaliana* was high under P deficiency. Oilseed rape was reported to contain large amount of P as compared to maize despite having less root and shoot biomass Morel and Hinsinger (1999), and this could be due to long root hairs of oilseed rape compared to maize (Gahoonia and Nielsen, 2004). Large differences in root morphology and distribution are present between genotypes of many plants (Bates and Lynch, 2001; Krasilnikoff *et al.*, 2003; Römer and Schenk 1998; Vance 2001). Root characteristics such as total root length, root hair length and density, and specific root length have been shown to vary considerably between genotypes of several species (Løes and Gahoonia, 2004; Nielsen *et al.*, 1997; Römer and Schenk, 1998;;

Singh Gahoonia *et al.*, 1997 ; Yan *et al.*, 1995). Significant differences in P uptake in cereal cultivars grown on low-P soil were reported due to differences in length of root hairs of these cultivars Singh Gahoonia *et al.*, (1997). Similarly, genetic differences in P uptake in cowpea and in maize due to variation in root length and root hairs have been reported (Krasilnikoff *et al.*, 2003). Maize genotypes modified their root architecture in response to low P in the rooting medium (Zhu *et al.*, 2005). Genotypes, which performed better under P-deficient conditions, develop shallow root systems to tap P accumulated in topsoil and have greater specific P absorption rate, tissue P contents, relative growth rate, and biomass accumulation than others (Zhu *et al.*, 2005). Phosphorus availability regulates different aspects of root architecture like axial extension, root branching, basal root gravitropic, the relative distribution of basal root length, and adventitious roots (Liao *et al.*, 2004 ; Miller *et al.*, 2003 ; Ochoa *et al.*, 2006). These differences raise the possibility of selection and breeding of crop genotypes having extensive root systems to cope with P deficiency in soils. Earlier studies showed that root growth (root size, root weight, etc.) positively correlated with biomass production in different crops (Barracough, 1984; Gill and Ahmad 2003; Kosar *et al.*, 2002; Olaleye *et al.*, 2011).

6.1. Influence of root plasticity and plant nutrient acquisition in phosphorus

Phosphorus (P) is one of the most growth-limiting macronutrients, and root systems display diverse morphological and physiological strategies to enhance its uptake at low and heterogeneous P availability in soil (Lambers *et al.*, 2006, 2013). For example, under P limitation, primary root growth is suppressed and the root architecture changes to a shallower root system featuring roots that are more lateral and increased root hair density. This enables the roots to explore a larger soil volume (Pe'et *et al.*, 2011). Root physiological strategies include exudation of various organic anions and release of extracellular phosphatases to mobilize the otherwise unavailable P in the rhizosphere (Lambers *et al.*, 2011; Richardson *et al.*, 2011).

An important root morphological trait, root hairs (single-cell extension of epidermal cells), contribute up to 80% to plant P uptake by increasing the root surface area and, hence, the contact space between root and soil for absorption (Jungk, 2001; Jakobsen *et al.*, 2005; Li *et al.*, 2014). Increased surface area with root hairs, in turn, contributes to the release of root-derived organics and phosphatases, which subsequently increase P acquisition. For example, barley roots possessing hairs radially extended the rhizosphere by three times as compared to the mutant lacking root hairs (Holz *et al.*, 2018). Another important root functional trait with complementary function (increased P acquisition) is root colonization by arbuscular mycorrhizal fungi (AMF) (Munyanziza *et al.*, 1997). Plants trade carbon (C) to AMF for in exchange of nutrients. The extraradical mycelia of AMF may also enter the very fine soil pores, thereby increasing the nutrient uptake (Khalvati *et al.*, 2005). Here, we emphasize the rationale to consider root colonization with AMF as a 'trait' because approximately 18% of angiosperm species (e.g., members of Brassicaceae, Chenopodiaceae, Cyperaceae, Zygophyllaceae families) lack any symbiotic associations with fungi and about 30% of angiosperm species establish other (than AMF) types of mycorrhizal associations (Brundrett, 2002; Brundrett and Tedersoo, 2019). Given that a fungus is considered as mycorrhizal only after its successful interaction with roots to form a specific type of symbiotic association, the consideration of root colonization by mycorrhizal fungi as a trait is highly feasible. Mycorrhizal symbiosis may trigger various adaptive strategies into plant such as changes in the root-to-shoot ratio Veresoglou *et al.*, (2012), root architecture and longevity Hooker and Atkinson, (1996), root length Camenzind *et al.*, (2016), and root diameter (Comas *et al.*, 2014). Such allometric changes are plant-species-specific and depend on the duration of the experiments as well as on the identity of the plant and its fungal partner identities (Veresoglou *et al.*, 2012). Much of this information is derived from plant phylogeny by determining changes in root morphological and architectural traits using phylogenetically independent contrasts (Comas *et al.*, 2014). Accordingly, an in-depth understanding requires empirical evidence. The notion that plants colonized with AMF increase their root diameter has been forwarded Brundrett and Tedersoo, (2019), but explicit observations are missing. Moreover, most studies on plant-mycorrhizal interactions have focused on one plant growth stage, almost ignoring the dynamics of nutrient acquisition related to plant phenology. Such temporal changes in plant microbial interactions are defined as a 'missing factor' and highlight the necessity of incorporating those in future ecological studies (Schofield *et al.*, 2018). Interactions between roots and microorganisms are established at early plant growth stages. At later stages, such interactions gain importance due to plant-growth-associated changes in root morphology, soil properties Philippon *et*

al., (2013); Wen *et al.*, (2017), and variation in rhizo-deposits quality and quantity Chaparro *et al.*, (2014). Intense competition between plants and soil microorganisms for limited nutrients also play a role (Kuzyakov and Xu, 2013). For example, root exudation changes with plant growth stage Chaparro *et al.*, (2014) and results in altered enzyme activities in rooted soil (Kumar *et al.*, 2018). Throughout the growth period, plants adapt their strategies to maximize nutrient uptake, but no explicit relationship between specific root traits and nutrient acquisition has been determined (Chen *et al.*, 2016). Such strategies are plant-species-specific and the causes of variations are not conclusive. For example, increased root hair length and density in Brach podium cultivars were insufficient to increase plant P uptake and must be combined with other root traits to enhance P acquisition (Zhang *et al.*, 2018). The present study focuses on the root trait plasticity for plant P acquisition in P-limited soil and on the response of these traits to increased P availability via P fertilization. To this end, maize with (wild type, WT) and without root hairs (roothairless3 mutant, *rth3*) were grown for 64 days in a climate chamber under controlled environmental conditions. Subsets of both genotypes were fertilized with KH₂PO₄. We hypothesized that **(a)** in P-limited soils and in absence of root hairs (key trait for plant nutrient acquisition), plant growth is maintained by shifting the root traits to attract colonization by AMF for P acquisition, whereas **(b)** with P fertilization, plants become less dependent on specific root traits for P uptake. This study provides the opportunity to understand the plants' P uptake strategies through plasticity in root traits at three plant growth stages (tillering, stem extension, maize heading).

Kumar *et al.*, (2019) reported that, many plants have developed complex nutrient acquisition strategies including altering root morphology, root hair formation or colonization by arbuscular mycorrhizal fungi (AMF) particularly under soil nutrient limitation. The interactions of these strategies and their plasticity are, however, affected by soil nutrient status throughout plant growth. Such plasticity is decisive for plant phosphorus (P) acquisition in P-limited soils. We investigated the P acquisition strategies and their plasticity of two maize genotypes characterized by the presence or absence of root hairs. We hypothesized that in the absence of root hairs plant growth is facilitated by traits with complementary functions, e.g., by higher root mycorrhizal colonization. This dependence on complementary traits will decrease in P fertilized soils. At early growth stages, root hairs are of little benefit for nutrient uptake. Regardless of the presence or absence of root hairs, plants produced average root biomass of 0.14 g per plant and exhibited 23% root mycorrhizal colonization. At later growth stages of maize, contrasting mechanisms with functional complementarity explained similar plant biomass production under P limitation: the presence of root hairs versus higher root mycorrhizal colonization (67%) favored by increased fine root diameter in absence of root hairs. P fertilization decreased the dependence of plant on specific root traits for nutrient acquisition. Through root trait plasticity, plants can minimize trade-offs for developing and maintaining functional traits, while increasing the benefit in terms of nutrient acquisition and plant growth. The present study highlights the plasticity of functional root traits for efficient nutrient acquisition strategies in agricultural systems with low nutrient availability

They also concluded that function of root traits and their plasticity are crucial for plant P uptake in P-limited soils. The absence of root hairs induced an increase in the average fine root diameter thereby promoting root mycorrhizal colonization by AMF, Fig. (19). In turn, the presence of root hairs decreased the dependency of plants on root mycorrhizal colonization for plant P acquisition. Reduced colonization after P fertilization highlighted the maize plant's resource allocation by lowering trade-offs for P acquisition. Overall, maize alters its root morphology and biological traits as a nutrient acquisition strategy to maximize benefits and therefore, growth.

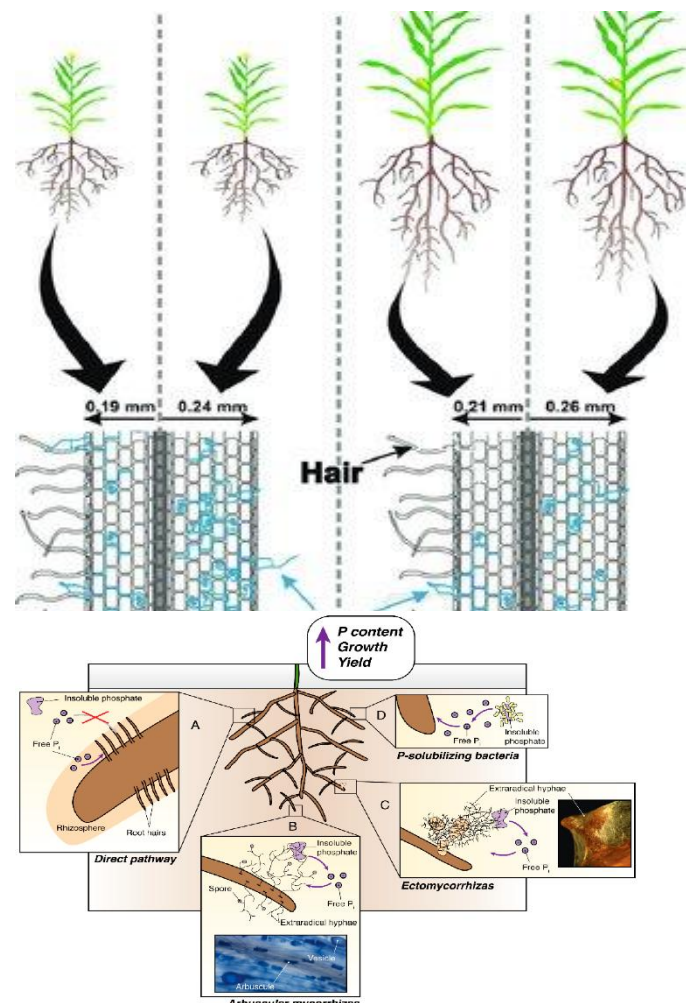


Fig. 19: Illustrates root traits in the presence (WT) and absence (*rth3*) of root hairs. When root hairs are absent, maize plants increased the average fine root diameter to facilitate root colonization by arbuscular mycorrhizal fungi to maintain P acquisition and growth. After Kumar *et al.*, (2019), Kafle *et al.*, (2019)

7. Water Use Efficiency Under Elevated CO₂

Water shortage present one of the primary world issues, and according to climate change projections, it will be more critical in the future. Since water availability and accessibility are the most significant constraining factors for crop production, addressing this issue is indispensable for areas affected by water scarcity. Because of increasing water scarcity and drought, resulting from climate change, considerable water use for irrigation is expected to occur in the context of tough competition between agribusiness and other sectors of the economy. In addition, the estimated increment of the global population growth rate points out the inevitable increase of food demand in the future, with an immediate impact on farming water use. Since a noteworthy relationship exists between the water possessions of a country and the capacity for food production, assessing the irrigation needs is indispensable for water resource planning in order to meet food needs and avoid excessive water consumption.

Hussain *et al.*, (2019), stated that water deficits pose a serious threat to crop productivity and food security in many parts of the world due to poor or erratic rainfall and depletion of groundwater reserves. Improving crop productivity under shortage water availability conditions is vital to meet global food demand (Balyan *et al.*, 2017). Agricultural production gradually required substantial amounts of water. Rahaman *et al.*, (2016) reported that to produce 1 kg of rice, consumed about 2497 liters. Therefore, improving rice genotypes with increased water use efficiency is essential without compromising yields (Shahane *et al.*, 2019). Climate change is predicted to increase the frequencies of droughts and floods, both of which will be problematic for food production (Mar *et al.*, 2018; Yao *et*

al., 2017). Recent strategies such as growth enhancements or increases in photosynthetic efficiency have the potential to increase intrinsic yields (Ambavaram *et al.*, (2014). Plant breeding is a good solution to accelerate the production of improved crop cultivars that are more tolerant to drought and other stresses.

High crop yield under optimal as well as environmental stress conditions is a valuable crop-stability trait that is targeted for improvement using classical breeding as well as genetic engineering (Century *et al.*, (2008). Many approaches have been proposed to boost intrinsic yield, such as enhancement of growth or increase in photosynthetic rate and capacity (Gibson *et al.*, 2011). Photosynthesis, the basis of life on earth that converts light energy to chemical energy in integrated photosynthetic carbon metabolism (PCM) processes, is complex and requires a systems-wide approach to coordinately improve plant productivity and yield Zhu *et al.*, (2010) that is stable under environmental stresses. Transcription factors (TFs) have shown promise in coordinately improving specific traits in rice, such as photosynthetic assimilation and plant biomass Karaba *et al.*, (2007) or grain yield (GY) components under drought Jeong, *et al.*, 2010), and have the potential to coordinately regulate photosynthesis and PCM for crop yield. Although photosynthesis is accepted as the basis of absolute yield, yield improvement via direct improvement of photosynthetic efficiency has not yet been successful (Taranto *et al.*, 2018). Nonetheless, evidence that elevated CO₂ can increase leaf photosynthesis in crops by as much as 22.6% over the growing season suggests that increasing photosynthesis can increase productivity and yield (Abdelrahman, *et al.*, 2018). One of the primary strategies has been on engineering RuBis CO to improve photosynthetic efficiency Spreitzer and Salvucci (2002), although many more metabolic reactions in PCM and associated processes in sucrose synthesis and photorespiration have been shown to play an equivalent role. Metabolic analysis using a dynamic model of PCM Zhu, *et al.*, (2007), suggests that the partitioning of resources among enzymes of PCM in C₃ crop leaves is not optimal for maximizing the light-saturated rate of photosynthesis and under elevated CO₂ predicted for the future, this problem is amplified. The selection of changes to the photosynthetic process intended to improve biomass production and crop yield must take into account a complex matrix of interacting genes and mechanisms. It is recognized that combining systems modelling with modern breeding and transgenic technologies holds promise to design new pathways, such as improved CO₂ fixation and photo respiratory pathways Kebeish, *et al.*, (2007), or new genetic-regulatory networks Barrett *et al.*, (2006) to improve photosynthetic efficiency. GY in cereals such as rice is limited by environmental stresses such as drought and high temperature, which are also increasing due to climate-change effects. Photosynthesis and related carbon metabolism is primarily affected by stress, thereby reducing GY (Chaves *et al.*, 2009). Understanding of this complex interaction in a systems biology approach will provide the genetic tools to maintain yield under stress. Amongst cereals, rice as a paddy field crop is particularly susceptible to water stress and it is estimated that 50% of the world rice production is affected by drought. Major research efforts are directed at understanding the mechanism of plant responses to drought stress to identify gene products that confer adaptation to water deficit. Molecular mechanisms of water stress response have been investigated primarily in the model plant species *Arabidopsis*. Upon exposure to drought-stress conditions, many stress-related genes are induced, and their products are thought to function as cellular protectors from stress-induced damage Oh *et al.*, (2009). The expression of stress-related genes is largely regulated by TFs. The rice and *Arabidopsis* genomes code for 41,500 TFs and about 45% of them are reported from plant-specific families. Various drought-stress studies have identified TF families with putative functions in drought including MYB, bZIP, Zinc finger, NAM and APETALA2 (AP2) (Oh, *et al.*, 2009). The AP2 family is one of the plant-specific TFs whose members share a highly conserved DNA-binding domain known as AP2, and members of this family have been associated with various developmental processes and stress tolerance (Haake, *et al.*, 2002). The AP2 TF CBF4, also known as DREB1, was shown by overexpression analysis to lead to drought adaptation in *Arabidopsis* (Haake, *et al.*, 2002). The *Arabidopsis* AP2 TF called HARDY was reported to provide enhanced drought tolerance and water-use efficiency (WUE) in *Arabidopsis* and rice (Karaba *et al.*, 2007). Ectopic expression of these genes confer drought tolerance and/or adaptation by modifying cellular structures of leaves and roots, CO₂ exchange and parameters such as WUE, which correlate with the transformed plants' ability to withstand drought. Taken together, these and other findings indicate that AP (Gibson *et al.*, 2011). TFs offer the potential to engineer plants in a way that makes them more productive under stress conditions. Although drought stress can alter the growth and development of a plant at any time during its life cycle,

water limitations during reproductive growth stages can be especially conducive to yield losses in crops such as rice and maize (*Zea mays*) (Zinselmeier *et al.*, 1995). Accordingly, the reproductive phases in these plants should be an important stage to study for identifying stress-responsive genes that might have a protective, or yield-altering, function in drought. Advances in plant genomics, including the availability of the complete genome sequence of rice, have provided an opportunity to identify stress-related TFs that control yield under drought. To this end, a genome-wide analysis of drought-stress responses was conducted and led to the identification of a candidate drought induced AP2/ERF TF in reproductive tissues. To determine whether the TF could play a role in enhancing the tolerance of rice and possibly other crops to drought stress, transgenic plants were generated that contain the candidate gene driven by the CaMV 35S promoter. The HYR (HIGHER YIELD RICE) gene-expressing transgenic plants here are referred to as HYR lines, as they showed higher GY under well watered and drought-stress conditions. In addition, the HYR lines expressed multiple component traits involved in photosynthesis, sugar levels, root and shoot biomass and WUE under well-watered and drought-stress conditions. The enhanced productivity and the drought-resistant phenotype of the transgenic plants compared with the wild type (WT) are discussed. These studies provide an insight into improvement of plant productivity through enhancement of photosynthesis and multiple downstream biological processes (BPs) in combination with stress tolerance in plants.

Several reports in this issue Kunert and Vorster, (2020), Melandri *et al.*, (2020a); Nutan *et al.*, (2020b); Sulpice, (2020); Zhu *et al.*, (2018), highlight the physiological, molecular, and biochemical responses of plants to drought stress. A metabolite profiling analysis of the flag leaves of 292 *indica* rice accessions has led to the identification of new molecular markers for drought tolerance and sensitivity in terms of grain yield (Melandri *et al.*, 2020a; Sulpice, 2020). Melandri *et al.*, (2020a), highlights the central role of the ascorbate–glutathione cycle and of lipid peroxidation in mitigating drought-induced yield losses. Dehydroascorbate reductase activity and malondialdehyde levels were shown to be accurate biomarkers for drought tolerance. These markers have potential use in breeding for improved rice grain yield stability under drought condition. Melandri *et al.*, (2020b) report an association mapping and genetic dissection study of drought-induced canopy temperature differences in rice in another paper. Intriguingly, these authors report that low canopy temperature is a useful indicator of access to moisture during drought (Kaler *et al.*, 2018). Kamburova *et al.*, (2017) stated that an important strategy for soybean yield improvement. These authors have identified quantitative trait loci (QTLs) regulated by slow canopy wilting (SW) in late maturing soybean genotypes Abdelrahman *et al.*, (2018). The SW trait, which is associated with drought tolerance, involves at least two distinct mechanisms: water use efficiency and conservation. Since drought already causes ~ 40% reduction in soybean yields Specht *et al.*, (1999), the findings reported by Abdelrahman *et al.*, (2018) represent an important new direction of research Kunert and Vorster, (2020), have identified genetic resources for improving drought tolerance in early maturity group soybeans.

7.1. Irrigation water in agricultural lands under climatic changes.

Qadir *et al.*, (2003) stated that the import-export of virtual water could help to alleviate the future increase of water demand for food, due to climate change impacts and population growth. Increasing water scarcity and drought condition, however, point to the necessity for a more sustainable approach to water resource management in agriculture at the global, regional and local level. However, in some countries such as the Mediterranean region, irrigation is mainly applied during the summer, which coincides with the main tourism period and results in a competition between these two sectors. This aspect highlights the necessity of water resource planning to allocate water supply among different economic sectors. First step in the agricultural sector is to compute how much water crops with regard to climate conditions need. Some techniques, such as soil monitoring, lysimeters, eddy covariance, the Bowen ratio and surface renewal, are used to monitor and measure irrigation needs. While the monitoring approach may require delicate and expensive sensors or the assistance of experts, the application of models (e.g., soil water balance models) could provide a low-cost method for on-farm and regional systems for computing the crop water requirement and estimating the depth of water storage required to satisfy the agricultural demand. Once the crop water requirement is known, improving the efficiency of the irrigation application is a key strategy for water savings in agriculture. The term “efficiency” is commonly used to indicate “the level of performance” of a system. In the

agricultural sector, the concept of “water use efficiency” is often used to highlight the relationship between crop growth development and the amount of water used.

Sinclair *et al.*, (1983) described plant water use efficiency as the ratio of biomass accumulation (expressed as carbon dioxide assimilation), total crop biomass or crop grain yield to transpiration by the crop.

Nowadays, many strategies are implemented to improve water productivity, starting with the optimal choice of irrigation system, followed by the application of the proper irrigation scheduling in terms of both timing and quantity of water applied and concluding with the choice of the best crop management concerning the soil and climate conditions. The selection of the proper irrigation system depends on several factors, such as water availability, crop selection, soil characteristics such as deep percolation, runoff, evaporation rate and topography and the associated installation and maintenance costs. The main systems are separated into gravity systems, where water moves naturally over the soil surface due to the force of gravity, and pressurized systems. Burt *et al.*, (1997) describe several measures of irrigation efficiency. An important measure to evaluate the performance of irrigation systems is the application efficiency (AE), which is defined as the ratio of the average depth of irrigation water contributing to the target divided by the average depth of irrigation water applied. The target depth is generally based on the soil water depletion before irrigation or a smaller amount to adjust for rainfall contributions. The target can also include excess water for reclamation or for salinity control. Many studies have been conducted to determine the AE for different systems, and the overall conclusion is that pressurized systems are generally more efficient for transporting water to crops than traditional gravity systems (Chimonides, 1995).

In recent years, several irrigation systems have significantly improved the application efficiency at the farm level, enhancing irrigation water management. Although the traditional gravity approach is still widely used Abou Seeda *et al.*, (2020), particularly, in the southern part of Europe, it is gradually being replaced (European Environment Agency (EEA) (2009). Abou Seeda *et al.*, (2020) nevertheless, the application efficiency of a system depends on the amount and timing of water applied, as well as on the considered crop, soil and climate conditions. To maximize crop yield and meet the crop water requirement, irrigation to refill soil water depletion is typically applied at each irrigation. This approach is valid for most field crops and many orchard crops. Holzapfel *et al.*, (2009), however, indicated that providing deficit irrigation to some tree and vine crops can lead to more profits due to a small reduction in yield, but better quality and reduced water application. Improving the crop technical efficiency may be another solution to overcome the water for food issue. The choice of the best cultivar, such as more drought-tolerant cultivars, or crop management concerning the soil and climate conditions can provide a method to improve water productivity.

7.2. Climate change affects soil salinity in agriculture soils

Climate change is defined by: high atmospheric CO₂ (i.e. >400 ppm); increasing air temperatures; abrupt and significant changes in daily, seasonal and between-year temperature; changes in wet and dry cycles; intensive rainfall events; extended drought periods; extreme frost; and hot, dry spells that elevate fire hazard levels. Changes in climatic patterns are expected to significantly influence terrestrial systems, soil properties, surface waters and stream flows (Patterson, *et al.*, 2013). High levels of uncertainty exist in climate model projections, particularly at regional and local scales, but climate change models do agree on some basic global trends. The models indicate that climate change is expected to affect primarily precipitation, potential evapotranspiration (ET) and temperature. Changes will occur in irradiance, ultraviolet irradiance and evaporative demand, as well as on the secondary factor ozone (Yeo, 1999).

Climate change models suggest **(a)** an increase in the average global temperature, **(b)** altered weather patterns with shifts in rainfall patterns, and **(c)** an increase in climatic extremes within localized areas (Yeo, 1999). Increased global temperatures will raise ocean levels as polar ice caps melt and will bring more extreme weather conditions. Droughts and flooding are expected to increase in frequency and intensity. Hot dry areas are expected to become hotter and drier, some wet areas wetter, and isolated cold areas will be colder. There is an expectation that climate change will bring increased frequency of extreme weather events around the globe, with unusually high rainfall events leading to floods and low precipitation, higher temperatures, and higher potential ET resulting in longer, harder and more frequent droughts.

The National Center for Atmospheric Research released a collection of drought severity maps projecting drought levels using the Palmer Drought Severity Index for the period 2000–2099. The drought maps show that much of the Western Hemisphere and large parts of Eurasia, Africa and Australia will experience extreme drought, whereas higher-latitude regions from Alaska to Scandinavia are likely to become wetter and experience flooding. Evidence of the impact of the change on climate patterns is found worldwide. For instance, the USA experienced an increase in moderate to severe levels of drought, particularly in the southwest, but other areas are not exempt (e.g., the Midwest and southeast). Arguably, the most notable from a public-awareness perspective, due to its impact on agricultural productivity, was the California drought of 2011–2015. This caused drastic reductions in irrigation water allocations to farmers in the agriculturally productive San Joaquin Valley (SJV) and heightened water conservation measures in urban areas.

Other recent worldwide droughts include a 1 in a 1000-year drought in Australia (e.g., lower portion of the Murray-Darling River Basin), which began in 1995 and continued until 2009; Spain's drought in Catalonia; northern India's drought in the first decade of the new millennium; and droughts in northern China, Syria and southeastern Brazil. Recent floods include Queensland, Australia; Tennessee, Arkansas, Texas and Wisconsin in the USA; Pakistan; and India. Even though there is no short-term extreme weather event that can be conclusively attributed to climate change, there is a statistical record of these events showing that they clearly occur with increased frequency and/or intensity (Dai, 2011). Ironically, some of the most crop-productive areas of the world occur in water-scarce regions, such as the arid southwestern USA e.g., California's San Joaquin and Imperial-Coachella Valleys and other arid regions of the world, including the Middle East, the Hai He, Huang He and Yangtze basins in China, and along the Nile River in Egypt and Sudan.

In most cases, these areas owe their successful crop productivity to mild year-round climates and available sources of surface water and/or groundwater for irrigated agriculture. Climate change will influence global rainfall patterns, affecting both the amount and distribution of rainfall. Global climate change model predictions indicate decreased precipitation for drier regions of the world, with annual average precipitation decreases likely to occur in most of the Mediterranean, north and south Africa, northern Sahara, Central America, the American southwest and the southern Andes, as well as southwestern Australia (Collins *et al.*, 2013). Arid regions are the most prone to desertification and salinization (Geist, 2005; Szabolcs, 1990). Agriculture is directly linked to climate change. Crop yield, water use, biodiversity and soil health are directly affected by changes in the climate. Changes in the frequency and intensity of rainfall, temperature and other extreme weather events will influence agricultural productivity, with the net effect of climate change on world agriculture most likely to be negative. Even though some regions and crops may benefit from increased CO₂, many will not.

Increasing of CO₂ atmospheric are likely to increase organic matter in soil and stimulate growth and improve water-use efficiency in some crops, but heat waves, droughts and flooding may dampen these potential yield increases. Recent research has indicated that increasing atmospheric CO₂ may not have as large influences on plant and crop productivity as once thought (Jarvis, *et al.*, 2010; Körner, 2006; Long, *et al.*, 2005; Poorter and Navas, 2003; Zaehle, *et al.*, 2010; Zavaleta *et al.*, 2003). Ostensibly, increasing ozone levels may counteract the CO₂ effect (Long *et al.*, 2005). The negative effects of increased temperature on plant growth may also counteract the CO₂ effect (Jarvis *et al.*, 2010). Furthermore, indirect climatic impacts, such as greater competition by insects, weeds and pathogens, will decrease yield.

Higher atmospheric CO₂ concentrations, higher temperatures, more intensive rainfalls and extended droughts and heat waves will accelerate weathering of rocks and minerals in soils either chemical or physical; both are effective on weathering processes. In a 44-year field study by Gislason *et al.*, (2009), weathering rates were found to be already increasing because of global warming. There are both positive and negative effects of climate change induced accelerated weathering. Accelerating weathering can increase the inorganic carbon pool in soils due to carbonate mineral formation, which will help decrease atmospheric CO₂ levels. In addition, the dissolution of elements that serve as nutrients for microbes and plants will stimulate microbial and plant growth and biotic C sequestration, which will help decrease atmospheric CO₂ levels (Qafoku, 2014). In contrast, accelerated weathering may perturb the balance of the biotic and in arid and semi-arid regions, soil salinity and irrigation management go hand in hand because salinity control is generally a consequence of leaching. Soil

salinity refers to the concentration of salts in the soil solution, consisting of four major cations such as Na^+ , K^+ , Mg^{+2} and Ca^{+2}) and five major anions as HCO_3^- , Cl^- , NO_3^- , SO_4^{-2} and CO_3^{-2}).

Soil salinity is characterized in terms of the concentration and composition of the soluble salts and is most commonly measured in the laboratory as the electrical conductance of the saturation extract in dS m^{-1} (Corwin and Yemoto, 2017). The accumulation of soil salinity could reduce plant growth, yield production, and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic potential, making it more difficult for the plant to extract water. Salinity may also cause specific ion toxicity effects e.g., Na^+ ion toxicity depending on the soil pH and upset the nutritional balance of plants. The salt composition of the soil water influences the composition of cations on the exchange complex of soil particles, which influences soil permeability and tilth. Sodic soils have soil structure degradation and permeability reduction.

Furthermore, soil salinization is driver for desertification phenomena and creating land degradation processes such as arable land abandonment and soil erosion (Qin *et al.*, 2013). Because of the potential detrimental impacts of soil salinity accumulation and its ubiquitous association with irrigated agriculture, salinity is a soil chemical property that is crucial to soil health. The impact of climate change on soil salinity levels in the root zone has been far less studied than other soil properties, such as organic matter, N and P. This may be because salinity is among the most spatially complex and temporally dynamic soil properties, with a coefficient of variation generally over 60% (Corwin *et al.*, 2003). Another reason may be the lack of quantitative spatial data over large spatial extents to make comparisons of changes over time. Salt-affected soils are estimated to comprise 23% of the cultivated land, approximately $3.5 \times 10^8 \text{ha}$ (Massoud, 1981).

However, no directly measured global inventories of soil salinity, all known global inventories of soil salinity and, with only one exception, all known regional-scale inventories are gross approximations based on qualitative and not quantitative data (Lobell, 2010; Lobell *et al.*, 2010). Until the recent development of proximal and remote sensors with associated protocols and guidelines for measuring soil salinity from field to regional scales, the ability to map and monitor soil salinity across multiple scales has been too formidable due to the high spatial and temporal variability of soil salinity (Corwin and Scudiero, 2016). Alternatively, because, unlike many other soil properties, soil salinity can be easily managed by the addition of water to leach salts. As long as the water source is plentiful and sufficiently good in quality, then salinity is generally not regarded as a problem of concern. However, if droughts become more frequent as climatologists predict, then salinity is likely to become a growing issue of concern. Global food security focuses on four major crops that account for 85% of the world's cereal exports: wheat, rice, maize and soybean (Teh and Koh, 2016). Past climate change, trends in crop production are evident in several regions across the globe Lu, *et al.*, (2013). Lobell *et al.*, (2011) provided evidence that climate change had already affected wheat and maize yields both regionally and globally. The expectation is that climate change will fundamentally alter the patterns of global food production, with negative impacts on crop productivity of wheat, rice and maize in low latitude and tropical regions (FAO, 2016). Temperate zones will also be impacted, such as for maize in the USA and wheat in the European Union, due to increased water scarcity, more frequent and intense heat events, and accelerated phenology (FAO, 2016).

Even though most climate change impacts on crop productivity are expected to be negative, there are studies that predict positive impacts in areas where increases in precipitation are expected to occur. For instance, the combined use of climate and crop models for the grain-producing zone of Central Eurasia indicates an increase in yield because of higher atmospheric CO_2 , warmer temperatures and longer growing seasons with less frost

According to climate models, the Mediterranean Basin will increase in winter temperatures combined with altered rainfall patterns and changes in rainfall amount (Qafoku, 2014). The Gaza Strip, like most arid and semi-arid agricultural areas within the Mediterranean Basin, has serious water-deficit problems regarding both quantity and quality (Massoud, 1981; Zheng, *etal.* 2009). Over 70% of the total groundwater extracted in the Gaza Strip is used for agriculture (Corwin and Yemoto, 2017). Simulations of seawater intrusion by Loáiciga *et al.*, (2012) showed that groundwater extraction is a significant factor in seawater intrusion.

The relationship between Na^+ , Cl^- and the spatial variation of ionic ratios of $rCa^{2+} = (rHCO_3^- + rSO_4^{2-})$ in coastal areas of the Gaza Strip show that the aquifer currently used as an irrigation water source exhibited seawater intrusion (Benbi and Kaur, 2009; Corwin and Yemoto, 2017). It is expected that seawater intrusion in the Gaza Strip and throughout the Mediterranean Basin will be exacerbated by several climate change projections: (a) air temperature will increase from 2. to 5.1°C, (b) precipitation will decrease from 4 to 27%, (c) drought periods will increase, with a higher frequency of days exceeding 30°C, and (d) sea level will increase by around 0.35 m, with a concomitant increase in seawater intrusion (Loáiciga *et al.*, 2012). These projected changes in climate for the Mediterranean Basin will have an impact on salinity accumulation due to seawater intrusion, which will influence crop productivity and directly affect crop yield (Corwin and Yemoto, 2017). found that in the Gaza Strip the impact of an increase in salinity on irrigation requirements is considerably higher than the impact of climate change.

8. Impact of Climate Change on Soil Health

Several manuscripts in this issue focus on different aspects of climatic change impacts on soil physical properties hear however, chemical parameters were completely discussing during the subtopics in our review. Several manuscripts in this issue focus on different aspects of climatic change impacts on soil physical properties hear however, chemical parameters were completely discussing during the subtopics in our review. The potential impact on soil health resulting due to the climate change is through organic matter supply, temperature regimes, hydrology and salinity. Following are the major consequences of global climate change on soil health. Some soil physical properties such as (Soil texture and structure, creating type of soil porosity influences on water infiltration and water available for plant, bulk density, rooting depth, type of vegetation, Soil temperature). Higher temperature, high and low extremes of rainfall, increase in CO₂ concentration and their interactions due to climate change are expected to influence on several soil physical process which will subject the soils to significant risk of salinization, decreased water availability and changes in C and N dynamics, nutrient storage in soil and reduction in soil biodiversity (Benbi and Kaur, 2009). The physical properties and processes of soil affect soil health by altering water movement through soil, root penetration in soil and water congestion, some of climate change are as follow.

8.1. Soil texture

Soil texture is the relative proportion of soil competence such as sand, silt and clay fraction that has direct impact of climate change. The four potential climate scenarios (Arid, Semi-arid, Sub-humid and Humid) have great impact on important soil processes as the texture differentiation in the soil profile (Brinkman and Brammer, 1990; Scharpenseel *et al.*, 1990).

8.2. Soil structure and aggregate stability

Soil structure defined by arrangement and organization of primary and secondary particles in a soil mass, therefore controlling water and air present in soil pores.

Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. The space between the aggregates provides pore space for retention and exchange of air and water. Aggregation affects erosion, movement of water, and plant root growth. Desirable aggregates are stable against rainfall and water movement. Aggregates that break down in water or fall apart when struck by raindrops release individual soil particles that can seal the soil surface and clog pores. This breakdown creates crusts that close pores and other pathways for water and air entry into a soil and restrict emergence of seedlings from a soil. Optimum conditions have a large range in pore size distribution. This includes large pores between the aggregates and smaller pores within the aggregates. The pore space between aggregates is essential for water and air entry and exchange. This pore space provides zones of weakness through which plant roots can grow. If the soil mass has a low bulk density or large pore spaces, aggregation is less important. For example, sandy soils have low aggregation, but roots and water can move readily (Dalal and Moloney, 2000; Moebius *et al.*, 2007).

The nature and quality of the structure is strongly influenced by the amount and quality of organic matter present, inorganic constituents of the soil matrix, cultivation methods and natural physical processes such as shrink-swell and freeze thaw behaviour. Deceasing of soil organic matter levels

decreasing in soil aggregate stability, infiltration rates and increase in susceptibility to compaction, runoff furthermore, susceptibility to erosion (Bot and Benites, 2005; Karmakar *et al.*, 2016).

8.3. Soil porosity

A measure of the void spaces in a material as fraction (volume of voids to that of total volume) and pore size distribution provide the ability of soil to store root zone water and air necessary for plant growth (Reynolds *et al.*, 2002). Pore characteristics are strongly linked to soil physical quality, bulk density, micro porosity and functions of pore volume. While soil porosity and water release characteristics directly influence a range of soil indices including soil aeration capacity, plant available water capacity and relative field capacity. Since root, development and soil enzyme activities are closely related soil porosity and pore size distribution. Moreover, because of future climate change scenarios (elevated CO₂ and temperature, variable and extreme rain fall events) may alter root development and soil biological activities. Soil porosity and pore size distribution consequently, soil functions are affected in unexpected directions. This aspects needs alteration in future studies on the relationship of soil health and climate change. Decreased microbial activity, reduced root growth and exudates, reduce aggregate stability, gradually increased rain fall intensities where rain droplets impact causes surface erosion and sealing on sodic soils. It will leads to poor crop emergence, growth and increases chances of surface runoff.

8.4. Infiltration and plant available water

The water availability for plant growth and important soil processes are governed by a range of soil properties including porosity, field capacity, lower limit of plant available water (thus, excluding osmotic potential), micro pore flow and texture (Jarvis, 2007; Reynolds *et al.*, 2002). Plant available water capacity has been used as part of integrative soil health tests to assess management impacts. Further, more the soil available water and distribution may respond rapidly to climate change, especially, to variable and high intensity rainfall or drought events and thus, management strategies, could be planting of cover crops, conservation tillage and incorporation of organic matter, that maintain or even enhance water infiltration and available water in soil may help in mitigating the impact of severe rainfall and drought events or severe erosion events (Lal, 1995; Salvador Sandris *et al.*, 2008).

8.5. Bulk density

Bulk density is routinely assessed to characterize the state of soil compactness in response to land use and management (Hakansson and Lipiec, 2000). Bulk density in general negatively correlated with soil organic matter (SOM) or soil organic carbon (SOC) content (Weil and Magdoff, 2004). The loss of organic carbon from increased decomposition due to elevated temperature Davidson and Janssens, (2006), may lead to increase in bulk density and hence, making soil more prone to compaction viz. land management activities and climate change stresses from variable and high intensity rain falls and drought events (Birkas *et al.*, 2009).

8.6. Rooting depth

Changes in rooting depth is likely to affect plant available water capacity, subsoil salinity, SOC content or other properties to indicate major constraints in the soil profile Birkas *et al.*, (2009); Dalal and Moloney, (2000). Under prolonged drought, the impact of sub soil constraints such as salinity and high chloride concentrations (Dang *et al.*, 2008; Box and Bruce, 1996) are likely to be greater on plant available water and hence plant productivity.

8.7. Soil surface cover (vegetation)

Soil surface cover provides range of important ecological functions including protection of soil surface water and nutrient retention, C- fixation and in some instances N fixation and support native seed germination (Box and Bruce, 1996). Soil structural conditions such as soil crust and soil seal formation, primarily related to sodicity are used to characterize soil health under climate change. The formation of soil crusts and seals can affect a range of soil processes, including water infiltration, oxygen diffusion, runoff, surface water evaporation and soil erosion.

8.8. Soil temperature

Soil temperature regime is governed by gains and losses of sun radiation at the surface, the process of evaporation, heat conduction through the soil profile and convective transfer via the movement of gas and water (Karmakar *et al.*, 2016). As with soil moisture, soil temperature is a prime mover in most soil processes. Warmer soil temperature will accelerate soil processes, rapid decomposition of organic matter, increased microbiological activity, quicker nutrients release, increase nitrification rate and generally accentuate chemical weathering of minerals. However, soil temperatures will also be affected by the type of vegetation occurring at its surface, which may change itself because of climate change or adaptation management.

9. Conclusions

Climate change represents one of the greatest research challenges currently faced by plant biologists, agronomists and conservation biologists. Greenhouse gas emissions set to continue to rise for the near future. Climate change has both direct and indirect impacts on agricultural production systems. Direct impacts include effects caused by a modification of physical characteristics such as temperature levels and rainfall distribution on specific agricultural production systems. Indirect impacts are those that affect production through changes on other species such as pollinators, pests, disease vectors and invasive species. These indirect effects can play a major role. They are much more difficult to assess and project given the high number of interacting parameters and links, many of which are still unknown

Climatic change can promote the accumulation of soluble sugar including glucose and fructose, and the accumulation of antioxidants including ascorbic acid, total phenols, and total flavonoids, but reduce the levels of protein, nitrate, Mg, Fe, and Zn in products. Nutrient deficiencies are one of the major causes of quality and production losses around the world, understanding the interaction of these stresses with eCO₂ is of paramount importance. Due to extreme weather, events the frequency of global warming is expected to increase that ultimately disturb the ecosystem globally. Living organisms e.g. plants, animals, fishes, and humans affected by the extreme environmental conditions. Food security and agricultural yield are considerably affected by the adverse weather. With elevation in temperature, the production of major crops has been reduced evidently around the world. The increased frequency of drought and heavy rainfall, temperature fluctuations, salinity, and insect pest attacks are anticipated to decrease crop productivity leading to higher threats of starvation. Crop adaptability has suffered not only because of temperature variations, but also because of rainfall

Climate change, it can also improve crop performance by increasing rates of photosynthesis and water-use efficiency, particularly, in C₃ plants. However, longer treatments with eCO₂ might lead to photosynthetic acclimation, due to increased soluble sugars leading to an imbalanced C: N ratio accelerated leaf senescence and/or limited growth, water deficit and temperature extremes owing to climate change; gradually influence the reproductive phase of plant growth. It was described that the flower initiation and inflorescence is badly affected by the water stress particularly, in cereals crops. Genetic mechanisms and of the physiological and molecular processes, determining mineral nutrients absorption are essential and will help to improve the nutritional performance of grains subject to climate change.

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