# Chapter 5
# Role of Global Climate Change in Crop Yield Reductions

**Gyan Prakash Gupta**

**Abstract** Uncontrolled emission of greenhouse gases (GHGs) leads to global warming and climate change. It is progressively changing at an alarming rate in the coming future. Increasing global warming is responsible for the difference in temperature, frequency of precipitation, drought events, and heat waves. By the end of the twenty-first century, the $CO_2$ crosses the concentration more than 600–1000 ppm, and it increases the temperature by 1–2 °C in tropical and subtropical countries. It is anticipated that food grain production would decline up to 30% depending on the plant group (C3 and C4 plant). This chapter deals with how C3 and C4 crop plant responds to elevated $CO_2$ and higher temperature. Increasing concentration of atmospheric $CO_2$ and higher temperature will promote or decrease crop growth period, development, quality, and yield. The various physiological processes like photosynthesis, respiration, and stomatal conductance are the sole mechanisms for endorsing crop growth. C3 crops grown from ambient (360 ppm) to high (720 ppm) $CO_2$ concentrations initially enhances the net $CO_2$ fixation and growth by nearly 30% but later on it reduced in photorespiration processes. Hence, $CO_2$ acclimation lowers down the overall shoot nitrogen concentrations. Later on, this led to a reduction in protein content and ultimately affected the plant growth rate and biomass, whereas even under the ambient $CO_2$, the C4 plant assimilation capability becomes saturated. The higher temperature will be responsible for heat shock injury as well as biochemical and physiological changes. Subsequently, it reduced grain production and yield depending on the geographical place. The higher temperature influences and maintains the equilibrium between C3 photosynthetic carbon assimilation and photorespiration process. It is predicted that after the interaction of atmospheric $CO_2$ and temperature under experimental conditions, C3 plants more favored under elevated $CO_2$ whereas, C4 plant more favored under higher temperature. There is a need for mitigation and adaptation strategies to improve agricultural crop production and minimizes the production risk for sustainable development.

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## 5.1 Introduction

Climate change, as a result of global warming are progressively changing at an alarming rate due to augmented emission of greenhouse gases (GHGs) such as $CO_2$, $CH_4$, and $N_2O$ from anthropogenic sources (fossil fuel combustion) (IPCC 2014). The foremost anthropogenic GHG is $CO_2$ which cover 76% of the total concentration and 16%, 6.2%, and 2.0% from $CH_4$, $N_2O$, and CFC gases, respectively (IPCC 2014). During the period of times, its deposition in the atmosphere alters the atmospheric concentrations of GHGs pollutants. It increases infrared absorption radiation, which is redirected from the earth's surface and imbalances the total energy of our ecological system, however progressively causing the atmosphere warmer, so that increasing global warming contributes to global climate change (i.e., increased temperature, frequency of precipitation, drought events, and heat waves) (Venkataramanan 2011; IPCC 2013). It was reported that 45%, 35%, and 20% of $CO_2$ emissions were produced from coal burning, oil burning, and natural gas burning, respectively (IEA 2017). In 2017, the most significant contribution of global $CO_2$ emissions were 27%, 15%, 10%, and 7% from China, the United States, the EU, and India, respectively, and its cover is around 59%, while 42% contributed by rest of the countries. However, the principal controlling agent is $CO_2$ which is responsible for global warming. Since 1950, $CO_2$ concentration has raised in the environment by 30%, which is a substantial increase after the industrial revolution (Fig. 5.1). Before the preindustrial revolution (1750 AD), atmospheric $CO_2$ was ~280 ppm (Luthi et al. 2008). In the present scenario, April 2019 registered a daily average $CO_2$ concentration of 412 ppm at the Mauna Loa Observatory in Hawaii. By 2050, it is anticipated to reach between 443 and 541 ppm, whereas by the end of 2100, the range will be from 421 to 936 ppm. The warming of the earth environment increases by 0.84 °C (IPCC 2014) and the global average temperature will increase by 3.7–4.8 °C (IPCC 2014; Meinshausen et al. 2011; Hartmann et al. 2013). Therefore, instant and strategic need for collective efforts from all over the world to curb emissions to keep atmospheric $CO_2$ at the lower end of that range (approx 421ppm). Figure 5.1 showing the global carbon budget from the year 1870 to 2017 is an accumulative contribution from various sources and sinks. Here, 202 ppm $CO_2$ is emitted from the burning of fossil fuels and cement industries. These emissions were 63% higher than that of 1990, with a rate of 2.7% per year (CDIAC; Le et al. 2018a, b). If this rate continues, $CO_2$ emissions can surpass 100 $GtCO_2$ by the end of the twenty-first century, nearly threefold the present level of 36 $GtCO_2$/year and eventually it crosses the concentration which is more than 1000 ppm (Fuss et al. 2014). Change in land use pattern is an additional factor responsible for rising atmospheric $CO_2$. It contributed about 88 ppm $CO_2$ from 1870 to 2017 (Fig. 5.1). Whereas total $CO_2$ emitted and released into the environment

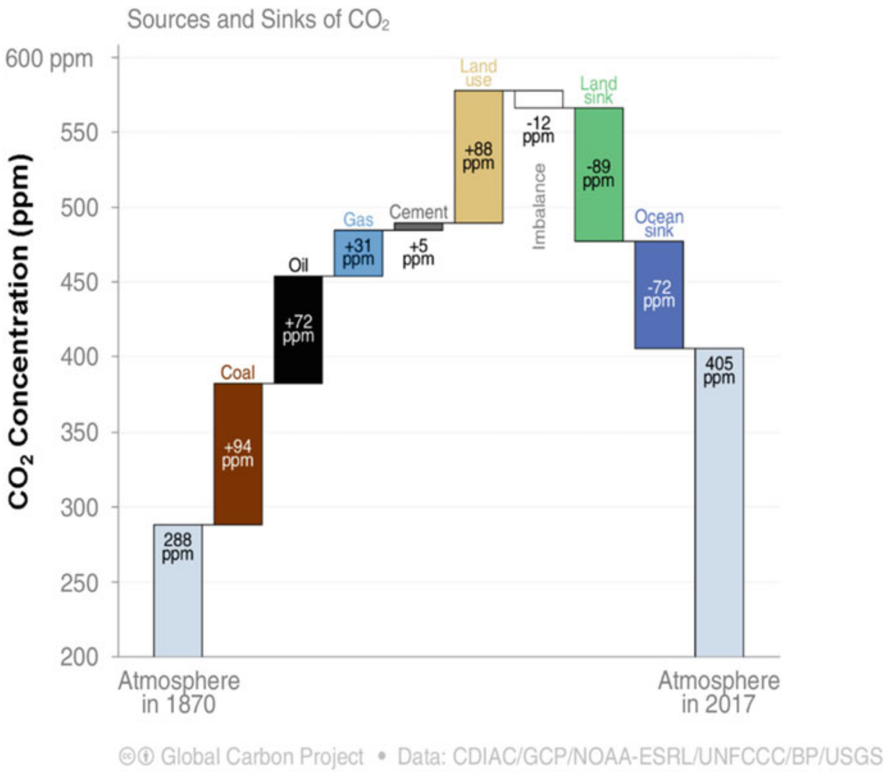



**Fig. 5.1** Global carbon budget from 1870 to 2017 (Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Le et al. 2018a, b)

during the last 145 years has not persisted there because of the ocean and land which act as sinks for gaseous $CO_2$. The land absorbs and fixes 89 ppm while oceans absorb 72 ppm $CO_2$ via various physiochemical processes, i.e., photosynthesis (Fig. 5.1).

Climate change raises the earth temperatures, drought and disturbed the monsoon patterns and the magnitude of air pollution that markedly affected the whole ecological function, human health as well as crop productivity of plant also (Bagley et al. 2015).

In this chapter, detailed description about C3 and C4 crop plant responses to elevated $CO_2$ and higher temperature is discussed. These responses are experimentally verified and tested in vitro as well as in vivo with the help of various physiological and biochemical parameters, which ultimately affected the crop yield and product quality. At the end, mitigation and adaptation strategies to improve agricultural crop production and minimize the production risk is also discussed.

## 5.2 Crop Response to Climate Change

In the present scenario, one of the most significant challenges is yielding ample food to meet the prerequisite of the rising world population. The issue of food security is further made intricate by climate change (Schmidhuber and Tubiello 2007; Cavagnaro et al. 2011). Elevated concentration of atmospheric CO2 at the end of the century, will promote or decrease crop growth period, development and yield which is dependent on the plant type, i.e. C3 or C4 plants (Poorter and Perez-Soba 2001; Leakey 2009). The plants are categorized into three groups based on the pathway that is used in reducing $CO_2$ to carbohydrate, i.e., C3, C4, and CAM plants. Photosynthesis, respiration, and stomatal conductance are the sole mechanisms for endorsing crop growth (Makino and Mae 1999). It led to morphological changes like leaf expansion, modification in shoot–root ratio, flowering, grain size, and yields (Masle 2000; Seneweera and Conroy 2005).

### *5.2.1 Effect of Elevated $CO_2$ on C3 Versus C4 Plants*

By the end of the twenty-first century, atmospheric $CO_2$ concentrations will increase by approximately 600–1000 ppm. The response of crops to increasing atmospheric $CO_2$ has been experimentally studied in a control growth chamber or greenhouses, open-top chamber and also using the Free Air $CO_2$ Enrichment (FACE) technology.

#### 5.2.1.1 Elevated $CO_2$ Affects Photosynthesis

##### 5.2.1.1.1 C3 Versus C4 Plants

The rate of $CO_2$ fixation through the photosynthesis process is dependent on available intercellular $CO_2$ concentrations (Ci). In the plant, there are two most common pathways to fix atmospheric $CO_2$, i.e., C3 and C4 pathway. The key differences between these pathways are not only based on the catalyzing enzymes and intermediary products but in terms of leaf anatomical feature also. Most of the crops follow the C3 path, where $CO_2$ is firstly fixed by Ribulose-1,5-bisphosphate (RuBP) and catalyzed by Ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) enzyme (Sage et al. 1989). This carboxylation reaction produces two molecules of 3-PGA (3-phosphoglycerate), a three-carbon stable compound and hence called a C3 plant. But, Rubisco also has oxygenase activity, by fixing $O_2$ in a light-dependent reaction releasing $CO_2$ when the internal concentration of $O_2$ is higher than that of $CO_2$. This fixation cycle is known as photorespiration and evolutionary adaptation mechanism toward oxygen level (Edwards and Walker 1983). Whereas, some crops use the C4 pathway, where $CO_2$ is firstly reacted and fix by Phosphoenolpyruvate (PEP), formed the malate or aspartate compound. It is a

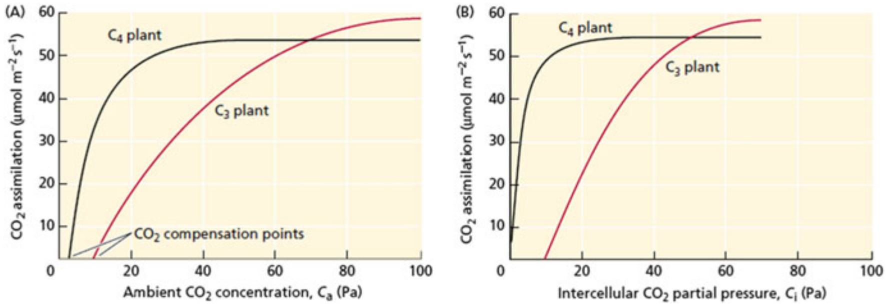



**Fig. 5.2** The variation of photosynthetic carbon assimilation rate is plotted against (**a**) ambient $CO_2$ in air and (**b**) intercellular partial pressure of $CO_2$ (Ci) inside the leaf of *Tidestromia oblongifolia* (C4 plant) and *Larrea divaricata* (C3 plant) (Berry and Downton 1982; Taiz and Zeiger 2014)

four carbon stable molecule and hence called a C4 plant (Taiz and Zeiger 2014). Here, the reaction is proceeded by PEP carboxylase, which does not have bi-functionality, and it has an affinity for $CO_2$ only (Blanke et al. 1987). In C4 species, leaf anatomy has anatomical specialization for $CO_2$ fixation by spatial segregation of photosynthesis, where mesophyll cell which is located peripherally is the site of $CO_2$ capture whereas the C3 cycle is operated in mesophyll cells, which surrounded the bundle sheath, is called Kranz anatomy. In these cells, the C4 molecule releases the $CO_2$ initially fixed in outer mesophyll cell; this facilitates higher concentrations of $CO_2$ around Rubisco enzyme and minimizes the oxygenase activity. Therefore, C4 plants are considered more efficient than C3 plants under ambient and intercellular $CO_2$ level because of well-designed $CO_2$ fixing mechanism (Edwards and Walker 1983) (Fig. 5.2a, b).

##### 5.2.1.1.2 Effect of Elevated $CO_2$ Enrichment on Crop Plant

It is reported and consistently shown that under elevated $CO_2$ condition it increased the photosynthetic carbon assimilation rate, therefore enhancing the growth of most plants but it depends on crops type (i.e., C3 or C4). The C3 plant has 33–40% increase as compared to C4 plant where it has only 10–15% increase in photosynthetic rate (Kimball 1983; Prior et al. 2003). But, increased $CO_2$ enrichment (i.e., 600–1000 ppm) can promote photosynthetic rate, especially of C3 plants. The higher atmospheric $CO_2$ is facilitated through the stomata and enter into the chloroplast of the mesophyll cell, where Rubisco enzyme enables carboxylation and decreases oxygenation process. Consequently, photorespiration process is hindered. Thereby, the yield of C3 crop plants is increased more than two- to threefold (Fig. 5.2a, b) (Jin et al. 2009; Lemonnier and Ainsworth 2019). Jin et al. (2009) observed that the yield of the Chinese cabbage leaf and stem lettuce increased twofold when grown between 800 and 1000 ppm $CO_2$. In onion, shoot and root dry mass increased under 700 ppm (Bettoni et al. 2014), whereas, in the case of Pea shoot growth and biomass production increased at 550 ppm (Butterly et al. 2016). Yields enhanced up to 44% in tomato, cucumber, and lettuce and 35% in French bean (Burkey et al. 2012; Korres et al. 2016).

In case of C4 plants, photosynthesis is saturated somewhat at the current atmospheric $CO_2$ level. Thus, C4 plant is not anticipated to benefit from changes in the atmospheric $CO_2$ levels. Leakey et al. (2009) observed that when maize plant is grown at irrespective varying concentrations of $CO_2$, photosynthesis rate constant (productivity) is not increased (Fig. 5.2a, b). But on the other hand, C4 crops might raise photosynthesis and yield indirectly via other factors such as anatomical adaptation, higher growth potential, and manage heat and drought stress (Leakey et al. 2009; Reich et al. 2015).

##### 5.2.1.1.3 Implication and Mechanism of Elevated $CO_2$ on C3 Versus C4 Plant

C3 crops grown from ambient (360 ppm) to high (720 ppm) $CO_2$ concentrations initially enhance the net $CO_2$ fixation and growth by nearly 30% but later on they reduce photorespiration processes (Woodward 2002). However, with continuous exposures for weeks of elevated $CO_2$ concentrations, the net $CO_2$ assimilation and plant growth slowdown and limit at the rates of average 12% (Curtis 1996) and 8% (Poorter and Navas 2003), respectively, as compared to plants kept at ambient $CO_2$ concentrations (Bowes 1993; Moore et al. 1998; Makino and Mae 1999). Consequently, $CO_2$ acclimation lowers down the overall shoot nitrogen concentrations, i.e., up to 14% (Poorter and Navas 2003; Makino and Mae 1999). Later on, this led to other responses like reduction in protein content and hampering the function of photosynthesis enzymes followed by affecting the plant growth rate and biomass (Long et al. 2004; Taub and Wang 2008). The reduction of shoot nitrogen concentration is explained by Rachmilevitch et al. (2004) and Bloom et al. (2014). In their experiment, they grew *Arabidopsis*, wheat, and peas under exposure of an elevated $CO_2$ concentration. Initially, biomass addition accelerated in 1 week but after 3 weeks, the plant started showing $N_2$ deficiency symptom and prevented for flowering and within 5–7 weeks exposure plant showing significantly reduced $NO_3^-$ reductase activity and diminishes $NO_3^-$ assimilation in the shoots and later on plant growth got hampered. It may cause and result in catastrophic loss of C3 plant. Several experiments and observation concluded that the elevated $CO_2$ increases the specificity of Rubisco carboxylase or Oxygenase so that photorespiration process inhibited and decreased the yield of C3 crops because $NO_3^-$ assimilation depends on photorespiration process (Bloom et al., 2010; Bloom et al., 2014; Kulshrestha and Saxena 2016). Thus, Rachmilevitch et al. (2004) and Bloom et al. (2014) proposed the three possible physiological mechanisms for the inhibitory effect of elevated $CO_2$ concentrations on $NO_3^-$ assimilation as: (1) The photorespiration process stimulates the transport of malate from the chloroplast into the peroxisome through the cytoplasm via malate shuttle, where it formed NADH, and it reduces hydroxypyruvate, and this malate shuttle is also helpful in the production of NADH/$NAD^+$ ratio in the cytoplasm (Backhausen et al. 1994) and NADH plays an essential role in the conversion of $NO_3^-$ to $NO_2^-$ (Quesada et al. 2000); (2) transport of $NO_2^-$ from the cytoplasm into the chloroplast stroma, and here the condition is that the stroma should be more alkaline than the cytoplasm whereas high concentrations of $CO_2$ somewhat increases the acidity after deposition in the stroma of the chloroplast (Shingles et al. 1996; Bloom et al. 2002); and (3) the chloroplast stroma competes for reduced ferredoxin (Fdr). It is an electron donor for the conversion of $NO_2^-$ to $NH_4^+$ whereas enzyme ferredoxin-NADP reductase (FNR) has a higher affinity for Fdr than nitrite reductase (NiR) so that elevated $CO_2$ can be more assimilated when the production of reducing NADPH is high and therefore, $NO_3^-$ assimilation proceeds if the availability of Fdr is more than needed for NADPH formation (Knaff 1996; Backhausen et al. 2000). Whereas, in C4 plants, $NO_3^-$ assimilation is not affected by elevated $CO_2$ because the cytoplasm of mesophyll cells itself maintains a sufficient amount of malate and NADH during the first step of carboxylation reaction during the $CO_2$ fixation pathway. That is why $NO_3^-$ assimilation in the shoot is independent of the elevated $CO_2$ (Bloom et al. 2012).

#### 5.2.1.2 Elevated $CO_2$ Affects Dark Respiration

Dark respiration is explained as $CO_2$ release or $O_2$ uptake after the oxidation of substrates through the pathway of glycolysis, the oxidative pentose phosphate pathway, and the Krebs cycle pathway linked to oxidative electron transport pathways of the mitochondrion. Respiration is a catabolic pathway that generates ATP and intermediate compound to fulfill the energy requirement for plant growth and development (Wang et al. 2001; Taiz and Zeiger 2014; Saxena and Sonwani 2019a, b). It may happen in the dark or the light period (Graham 1980). At elevated $CO_2$, when a crop will grow at night, dark respiration will be inhibited, and daytime photosynthesis is stimulated. Hence, the photosynthesis/respiration ratio will be increased and imbalance the carbon ratio of plants as well as environment also (Mattos et al. 2014). Table 5.1 shows the direct inhibition of dark respiration rate

**Table 5.1** Effect of elevated $CO_2$ on dark respiration in leaves of grassland species

| Species | Dark respiration rates (nmol $g^{-1}$ $s^{-1}$) | | | % change |
|---|---|---|---|---|
| | *n* | 360 (μmol $mol^{-1}$) | 700 (μmol $mol^{-1}$) | |
| C3 grass | | | | |
| *Agropyron repens* | 4 | 15.7 | 16.1 | 2.4 |
| *Bromus inermis* | 5 | 13.5 | 13.5 | −1.5 |
| *Koeleria cristata* | 4 | 12.4 | 12.4 | 0.1 |
| C4 grass | | | | |
| *Andropogon gerardii* | 6 | 17.4 | 17.4 | −0.3 |
| *Schizachyrium scoparium* | 5 | 15.3 | 14.5 | −4.9 |
| *Sorghastrum nutans* | 6 | 16.8 | 16.5 | −2.0 |

(+) indicates an increase, whereas (−) indicates an inhibition of respiration and their % change in leaves of grassland species after exposure of elevated and ambient $CO_2$, i.e., 700 and 360 μmol $mol^{-1}$ $CO_2$ (Tjoelker et al. 2001).

Similarly, depending on plant species like Sugar maple (Burton et al. 1997), Douglas fir (Qi et al. 1994), and Eastern white pine (Clinton and Vose 1999), dark respiration rates are observed to decline (Peet and Wolfe 2000; Hamilton et al. 2001; Griffin et al. 2001) or remain unchanged in Citrus and French beans (Bouma et al. 1997; Jahnke 2001) while in another species like soybean, dark respiration increases (Leakey et al. 2009a).

#### 5.2.1.2.1 Mechanism for Dark Respiration Inhibition

There are two plausible mechanisms proposed for dark respiration inhibition under elevated $CO_2$:

(a) Suppression of dark assimilation of $CO_2$ due to inhibition of PEP carboxylase enzyme (Gonzàlez-Meler et al. 1996; Van der Westhuizen and Cramer 1998).
(b) The activity of succinate dehydrogenase and cytochrome c oxidase enzymes are inhibited (Gonzàlez-Meler and Siedow 1999).

### 5.2.1.3 Elevated $CO_2$ Affects Stomatal Conductance, Water Use Efficiency, and Transpiration

Stomatal conductance (gs) measures the rate of $CO_2$ uptake and loss of water through the stomata. It depends on the density, size, and degree of opening of the stomata. For example, the extra open stomata permits higher conductance which leads to higher photosynthesis and transpiration rates. Bisbis et al. (2018) explain the conductance of close and open stomata under different environmental conditions. They showed stomatal conductance through the pictorial diagram of the lower surface leaf stomata and their interaction with various environmental factors like $CO_2$, temperature, water supply, and drought (Fig. 5.3). The stomatal conductance would be: (i) normal stomatal opening at ambient $CO_2$ concentration (400 ppm), i.e., regular gas exchange rate and water use efficiency (WUE); (ii) partial stomatal closure at elevated $CO_2$ level (500–900 ppm), i.e., decreased gas exchange resulted

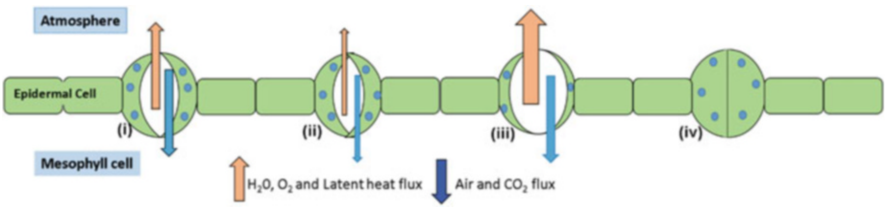



**Fig. 5.3** Schematic diagram of stomatal conductance (gs) under different environmental conditions (i.e., $CO_2$, temperature, and water)

in enhanced WUE and reduced transpiration; (iii) maximum stomatal opening at high temperature and adequate water flow, i.e., excessive transpiration and decreased WUE; and (iv) total stomatal closure at elevated temperature and drought, i.e., minimize transpiration losses to conserve water label inside the mesophyll cell.

At elevated $CO_2$, gs is generally reduced in most of the plants (Wand et al. 1999; Sonwani and Saxena 2016). There are various significant physiological and ecological consequences which lead to gs reduction, e.g., lower gs may change plant water label by reducing transpiration rate, increasing photosynthesis, and promoting the WUE. Consequently, it increases the productivity of many plants, especially of arid and semiarid regions (Owensby et al. 1999; Smith et al. 2000).

The mechanism behind is that at elevated atmospheric $CO_2$ levels (>400 ppm), a rise in leaf intercellular $CO_2$ (Ci) is shown. The internal Ci rapidly increases abscisic acid (ABA) in the guard cell within minutes, and this facilitates signal for reducing stomatal conductance (Mott 2009; Engineer et al. 2015). Carrot crop reduced their stomatal conductance by 17% and 53% at 650 and 1050 ppm, respectively, but $CO_2$ assimilation increased by 43% and 52% at 650 and 1050 ppm, respectively, in a growth chamber (Kyei-Boahen et al. 2003). In this way, elevated $CO_2$ leads to increase of WUE, but it enables crops to be more susceptible to heat shock too (Engineer et al. 2015).

#### 5.2.1.4 Elevated $CO_2$ Affects Product Quality and Yields

Elevated $CO_2$ affects the product quality as well as yields of many crop plants (Saxena and Naik 2018). Table 5.2 shows the influence of elevated $CO_2$ through changes in various physiological and metabolic processes that commence to the difference in the biochemical compounds like carbohydrate, protein, fatty acid, secondary metabolite, vitamins as well as a significant reduction and increase of micro- and macronutrients in different parts of the plants (Gruda 2009; Wang and Frei 2011). Becker and Klaring (2016) reported that the red leaf lettuce cultivated at elevated $CO_2$ (1000 ppm) has more concentration of caffeic acid, flavonoids, and sugars. Antioxidant compound (vitamin C) increased in the leaf and stem of celery, Chinese cabbage, and lettuce whereas soluble sugar increased in Chinese cabbage (Jin et al. 2009). However, several authors also reported a substantial reduction and increase in macro- and micronutrients in different crops (Pal et al. 2003; Shimono and Bunce 2009). Under elevated $CO_2$, the requirement and uptake of nutrients like N and P significantly increased because of vast amounts of these nutrients required in the photosynthetic and other metabolic processes (Ghannoum and Conroy 2007). In case of *Oryza*, total N uptake increased in the plant species, but N concentration decreased at the leaf level (Yang et al. 2007a; Ainsworth et al. 2007). In the case of P, the level increased (Yang et al. 2007b), lowered, or remained unaffected (Seneweera et al. 1994) whereas the level of Mg unchanged and Ca ion concentration increased in the leaf (Seneweera 2011).

Various studies also showed that elevated $CO_2$ substantially promoted the yield of different crops (Table 5.3). Maize yield increased by 50% (Rogers et al. 1983),

**Table 5.2** Effect of elevated $CO_2$ on crop quality

| Biochemical parameter | Experimental plant | $CO_2$ conc. | Effect | References |
|---|---|---|---|---|
| Sugars | Chinese cabbage<br>red leaf lettuce | 800–1000 ppm<br>1000 ppm | ↑ | Jin et al. (2009)<br>Becker and Klaring (2016) |
| Protein | Maize | 550 ± 20 ppm | ↓ | Abebe et al. (2016) |
| Antioxidant compounds | | | | |
| Flavonoid, phenols | Leaf spinach, lettuce | 700–1000 ppm | ↑ | Becker and Klaring (2016); Giri et al. (2016) |
| Ascorbic acid | Leaf and stem celery, lettuce, Chinese cabbage | 800–1000 ppm | ↑ | Jin et al. (2009) |
| Macronutrients | | | | |
| N, P, K, S, Mg | Spinach, lettuce | 700 ppm | ↓ | Giri et al. (2016) |
| N, P, K | Maize | 550 ± 20 ppm | ↓ | Abebe et al. (2016) |
| Ca | Rice | 700 ppm | ↑ | Seneweera (2011) |
| Micronutrients (Cu, Zn) | Lettuce, spinach | 700 ppm | ↓ | Giri et al. (2016) |
| $NO_3$ content | Leaf and stem Chinese cabbage, lettuce, celery | 800–1000 ppm | ↓ | Jin et al. (2009) |

27% (Cure and Acock 1986), and 22.9% (Meng et al. 2014) at elevated $CO_2$. Similarly, maize and sorghum grain yield increased by 18% at elevated $CO_2$ (550 ppm) (Long et al. 2006).

## 5.3 Effect of Higher Temperature on C3 and C4 Plants

### *5.3.1 Temperature*

It is a significant factor for crop's growth and development. According to seasonal crop plants, each has specific optimum temperature range requirements. The optimum temperature for warm-season crops or cold/hot-season crops are between 20 and 25 °C and hot-season crops is 25–27 °C (Wien 1997; Sonwani and Maurya 2018). The optimal average temperature of the individual plants is 18 °C for maize, 15 °C for wheat, 25 °C for cotton, 23 °C for rice, and 22 °C for soybean. The higher temperature will be responsible for heat shock injury as well as biochemical and physiological changes. Subsequently, it reduced grain production and yield depending on the geographical place (Lobell and Field 2007; Johkan et al. 2011). The temperature increased by 1–2 °C as a consequence of higher $CO_2$ in tropical and subtropical countries and it is anticipated that food grain production will decline up to 30% (IPCC 2014). Experimentally, maize plants are grown at 20–25 °C (day/night) and normal photosynthesis process is observed whereas if temperature

**Table 5.3** Growth yield of various crops toward elevated $CO_2$ concentration

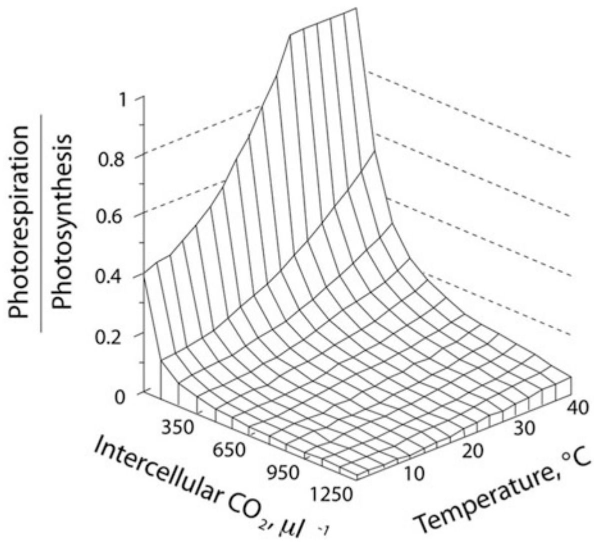
| Experimental plant | Crop yield (%) | References |
|---|---|---|
| *C4 crop* | | |
| Corn | 29 | Cure and Acock (1986) |
| Sorghum | 18 | Long et al. (2006) |
| Maize | 53 | Abebe et al. (2016) |
| *C3 crop* | | |
| Wheat | 35 | Cure and Acock (1986) |
| | 8 | Kimball et al. (1995) |
| Barley | 70 | Cure and Acock (1986) |
| Rice | 25 | Kimball (1983) |
| | 24 | Horie et al. (1996) |
| Soybean | 22 | Osborne (2016) |
| | 29 | Cure and Acock (1986) |
| | 45 | Baker et al. (1989) |
| | 22 | Fuhrer (2003) |
| Bean | 82 | Kimball (1983) |
| Green peas | 89 | Kimball (1983) |
| Groundnut | 31 | Clifford et al. (1993) |
| Tomato | 20 | Kimball (1983) |
| | 2–26 | Allen (1979) |
| Cucumber | 30 | Kimball (1983) |
| Lettuce | 35 | Kimball (1983) |
| Tobacco | 42 | Kimball (1983) |
| Sunflower | 144 | Allen (1979) |
| Potato | 51 | Kimball (1983) |
| | 43–75 | Allen (1979) |
| Radish | 28 | Kimball (1983) |
| Sweet potato | 83 | Cure and Acock (1986) |
| Quinoa | 12–44 | Bunce (2017) |

increases, i.e., 25–30 °C, the photosynthesis rate decreased by 30–60% (Ben-Asher et al. 2008). Similarly, Ruiz-Vera et al. (2015) also found a 5% reduction in photosynthesis at more than 25 °C temperature.

#### 5.3.1.1 Elevated Temperatures Affect Photosynthesis Versus Photorespiration Process

Temperature influences and maintains the equilibrium between C3 photosynthetic carbon assimilation and photorespiration process. It has mainly two methods. First one is, as the temperature increases, the solubility of $CO_2$ in mesophyll cell reduces as compared to $O_2$, hence internal concentration of $CO_2$ drops, and this brings about lowering the $CO_2$:$O_2$ ratio (Jordan and Ogren 1984; Taiz and Zeiger 2016; Saxena

**Fig. 5.4** Changes in the ratio of photorespiration to photosynthesis as a function of both $CO_2$ concentration and temperature for a plant with C3 photosynthesis (Ehleringer and Cerling 2001)

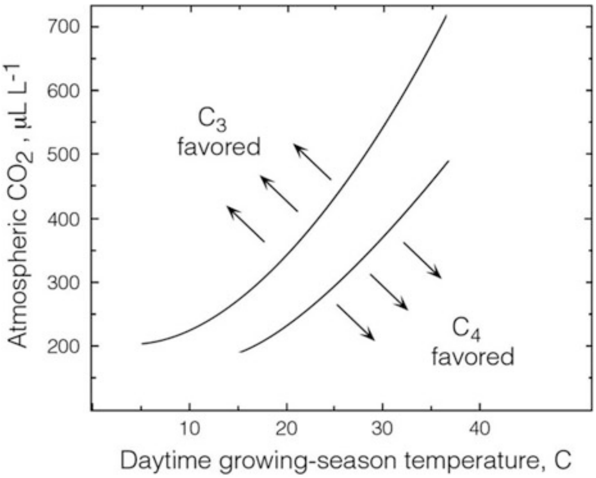



and Sonwani 2019a, b). The second one is that the enzymatic properties of Rubisco shifted more toward oxygenase activity as compared to carboxylase on account of increase in temperature, starting the photorespiration process over C3 carbon assimilation and initiating the fixation of $O_2$ to a higher degree than that of $CO_2$. In the C3 plant, the ratio of photorespiration to photosynthesis is dependent on increase in temperature and decrease of $CO_2$ or vice versa (Fig. 5.4). In this way, photosynthetic exchange of absorbed light into carbohydrate becomes less productive because there is a significant loss of $CO_2$ molecule in a C3 plant (Ehleringer et al. 1997; Taiz and Zeiger 2016). Based on the bi-functionality of RUBISCO (carboxylation/oxygenation) enzyme, C4 plants would be more promoted in that place where the average atmospheric temperature is higher than that of 25 °C (Taiz and Zeiger 2014; Ruiz-Vera et al. 2015) whereas, the average temperature for C3 crops is 18–25 °C. Hence, under low temperature and high atmospheric $CO_2$ preferred C3 plants (Wien 1997). Hence, C4 photosynthesis is preferred over C3 photosynthesis under the condition of high temperature and low atmospheric $CO_2$. Therefore, warmer temperature prefers C4 plant as compared to C3 plant (Fig. 5.5) because PEP carboxylase enzyme of C4 pathway is susceptible to low temperature and has good tolerance to high heat (Taiz and Zeiger 2016).

#### 5.3.1.2 Effect of Temperature on Phenology of Crop Plants

Climate and seasonal changes actively control plant phenology. Phenology is the study of episodic biological events, such as bud break, flowering, and fruit development. It became one of the most trustworthy bioindicators for climate change (Gordo and Sanz 2010). It has been understood through various studies related to

**Fig. 5.5** Interaction of atmospheric $CO_2$ and temperature that is predicted to favor C3 versus C4 crop plant (Ehleringer and Cerling 2001; Taiz and Zeiger 2016)




global warming which influences phenological measures for senescence, flowering, fruiting, and growth periods (Table 5.5) (Miller-Rushing and Primack 2008; Rumpff et al. 2010; Menzel et al. 2006a). There are several reasons pinpointed for the changes in the phenological features of the crops due to deviations in vernalization, photoperiodism, hormonal changes, or temperature or combinations of these aspects (Sparks et al. 2000; Rezaei et al. 2018). Only after exposure to a distinct number of days over a limited period of temperature, flowering is stimulated in determinate and indeterminate crops. After flowering, crop species terminate the vegetative growth and form fruits and end their life cycle after harvest (Peet and Wolfe 2000). In another way, global warming would fasten the growth of such crops and thereby curtail crop duration period for carbon fixation. On the one hand, it would be suitable for early maturation of plants, but on the other hand, it decreases or increases the product quality and yield (Laber and Lattauschke 2014) (Tables 5.4 and 5.5). For example, bean plant grew early but formed small seeds when grown at a temperature more than 27 or 22 °C (day/night) compared to 21 or 16 °C (Lattauschke 2015). In onions, higher temperature reduced the crop duration but yielded approximately twofold at 12 °C than that of 19 °C (Daymond et al. 1997). Elevated temperature also persuades flowering and fruit set through adverse impact on the physiological functioning of the reproductive organs. It affected double fertilization and reduction of lower husk cover and cereal development as well as fasten the sugar degradation and soften the texture of the fruit after harvest (Korner 2006;). For example, bean grown at elevated temperature triggered anomalous pollen, anther and ovule development and enhanced the flower abortion and fruit abscission (Abdelmageed and Gruda 2009).

**Table 5.4** High temperature effect on crops' product quality

| Parameter | Effect | Experimental plant | References |
|---|---|---|---|
| *External quality* | | | |
| Tipburn | ↑ | Lettuce, broccoli, Chinese cabbage | Saure (1998); Gruda and Tanny (2014) |
| Seed and fruit size | ↓ | Bean, pea, tomato | Siddique and Goodwin (1980); Lattauschke (2015); Gruda (2005) |
| Loose heads | ↑ | Broccoli, lettuce | Kałuzewicz et al. (2009) |
| Fruit coloration | ↓ | Tomato | Gruda and Tanny (2014) |
| Fruit cracking | ↑ | Tomato, pepper | Rosales et al. (2010); Gruda and Tanny (2014) |
| *Internal quality* | | | |
| Protein | ↓ | Wheat, rice | Myers et al. (2014) |
| Sugar content | ↓ | Pea, tomato, cabbage, sweet corn | Rosales et al. (2010); Gruda and Tanny (2014) |
| | = | Rice | Liu et al. (2017) |
| Starch | ↓ | Sweet corn | Wang and Frei (2011) |
| Macronutrients | | | |
| K, Mg, Fe, Ca | ↓ | Tomato | Rosales et al. (2010) |
| Fe | ↑ | Maize, soybean | Qiao et al. (2019) |
| P | ↑ | Maize, soybean | Qiao et al. (2019) |
| Ca | ↓ | Maize, soybean | Qiao et al. (2019) |
| Micronutrients | | | |
| Zn, Mn, Cu | = | Tomato | Rosales et al. (2010) |
| Fe, Mn | ↑ | Maize, soybean | Qiao et al. (2019) |
| Antioxidants | | | |
| Ascorbic acid (Vitamin C) | ↑ | Tomato, lettuce | Rosales et al. (2010) |
| | ↓ | Tomato | Wang and Frei (2011) |
| | = | Broccoli | Mølmann et al. (2015) |
| Tocopherol (Vitamin E) | ↑ | Lettuce | Wang and Frei (2011) |
| Lycopene Y | ↓ | Tomato | Gruda (2005); Rosales et al. (2010) |
| Carotene | ↓ | Carrot, tomato, lettuce | Ibrahim et al. (2006); Rosales et al. (2010); Wang and Frei (2011) |
| Anthocyanin, flavonols, phenols, glycosinolates | ↑ | Tomato, broccoli | Rosales et al. (2010); Gruda (2005); Mølmann et al. (2015) |
| Terpenes | ↑ | Carrot | Ibrahim et al. (2006) |

## 5.4 Interactions of Higher Temperature and Elevated $CO_2$ with Product Quality and Yield

Climate change as a result of elevated $CO_2$ increases the temperature and affects and interacts with the physiology of the crop in various ways. Their positive or negative interaction causes an impact on yield and product quality affecting through various physio-biochemical processes (Fig. 5.6) (Reich et al. 2015; Choi et al. 2011). It

**Table 5.5** Impact of elevated $CO_2$ and temperature on crop yield (Y, %)

| Crop | $CO_2$ (ppm) | Temperature (°C) | | | | | References |
|---|---|---|---|---|---|---|---|
| | | +1 | +2 | +3 | +4 | +5 | |
| Wheat | 660 | 25 | 16 | 2 | – | −32 | Lal et al. (1998) |
| | 555 | – | −8 | – | −39 | – | Siqueira et al. (1994) |
| | 515 | – | – | – | 21 | – | El Maayar et al. (1997) |
| | 630 | – | – | – | 9 to −20 | – | Adams et al. (1990) |
| | 550 | +5 to 25 | −35 | −10 to −50 | −15 to −70 | – | Rosenzweig and Tubiello (1996) |
| | 500 | | −10 to −12 | | | | Cai et al. (2015) |
| Soybean | 550 | +30 to 65 | | | | | Lenka et al. (2017) |
| | 555 | – | −3 | – | −11 | – | Siqueira et al. (1994) |
| | 515 | – | – | – | 23 | – | El Maayar et al. (1997) |
| | 630 | – | – | – | 49 to −20 | – | Adams et al. (1990) |
| | 660 | – | – | – | – | 40 to −20 | Adams et al. (1990) |
| | 585 | +2.4 | | | | | Ruiz-Vera et al. (2015) |
| | 700 | | 31 | | | | Qiao et al. (2019) |
| Maize | 550 | – | −9 | – | −20 | – | Siqueira et al. (1994) |
| | 515 | – | – | – | – | – | El Maayar et al. (1997) |
| | 630 | – | – | – | 49 to −20 | – | Adams et al. (1990) |
| | 660 | – | – | – | | 40 to −40 | Adams et al. (1990) |
| | 550 ± 20 | 54 | | 4.9 | | | Abebe et al. (2016) |
| | 700 | | 25 | | | | Qiao et al. (2019) |
| Rice | 660 | 4 | −5 | – | – | −25 | Lal et al. (1998) |
| | 500 | | −17 to −35 | | | | Cai et al. (2015) |

increases the leaf temperature and significantly impacts the photosynthetic capability, durability as well as it promotes the senescence and curbing the growing period and yield (Van De Geijn and Goudriaan 1996; Ruiz-Vera et al. 2015; Köhler et al. 2019). Table 5.5 shows the effect of temperature and $CO_2$ on crop quality in terms of morphological and biochemical changes. For example, higher temperatures increased loose and puffy heads, tip burn, yellowing and storage of secondary metabolite in cabbage crop (Wien 1997). Qiao et al. (2019) observed that the

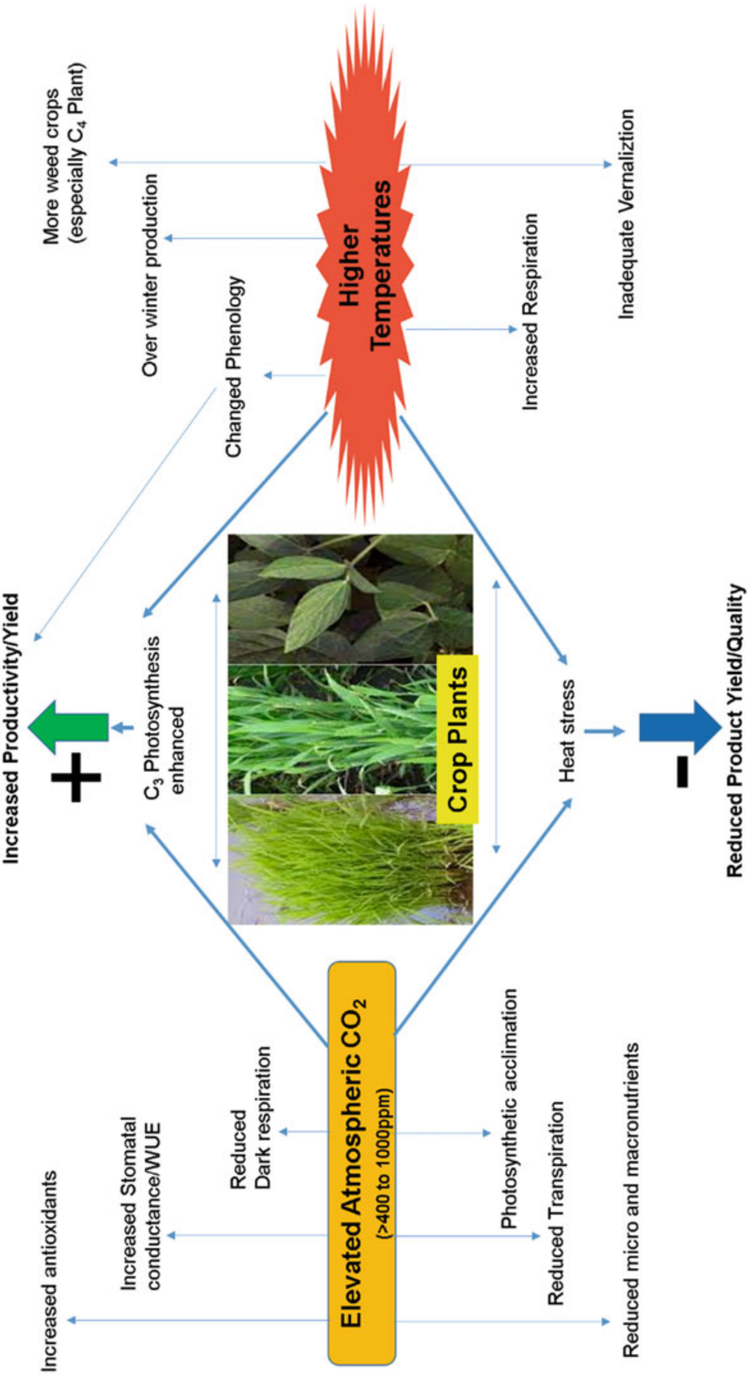



**Fig. 5.6** Interaction of elevated atmospheric $CO_2$ concentrations and higher temperatures on crop plant

concentration of oil in soybean was 9% and recorded 14% increase under elevated temperature (eT) and elevated $CO_2$ (eTe$CO_2$) whereas in maize grain 12% and 20% higher eT and eTe$CO_2$ as compared to control condition. Elevated temperature and $CO_2$ increase the content of macronutrients (N, P, and K), expand leaf area, number of grains per row and total yield of maize crop (Abebe et al. 2016). Table 5.5 shows the impact of elevated temperature and $CO_2$ on various crop yields %. There are several studies that show that high temperature and $CO_2$ and their interaction affect the yield of maize, wheat, and rice in positive or negative way with respect to growth period, product quality, and yield of abovementioned crops (IPCC 2007; Mendelsohn and Dinar 2009; Pathak et al. 2012; Ghannoum and Conroy 2007; Leakey et al. 2004; Fang et al. 2010; Pathak et al. 2012; Vanaja et al. 2015; Tripathy et al. 2009). The adverse effects of specific elevated temperature on the plant somewhat counterbalanced by high temperature along with elevated $CO_2$ concentration (Qaderi et al. 2006), whereas Qiao et al. (2019) reported that average yield of soybean was increased by 31% at elevated temperature and $CO_2$ but not at high temperature alone. But in case of maize, elevated temperature and $CO_2$ and elevated temperature alone both increased the yield by nearly 25% undergrown in open-top chambers (ambient +2.1 °C, 700 ppm $CO_2$). On the other hand, Abebe et al. (2016) reported that the yield and total biomass increased at elevated $CO_2$ with ambient +1.5 °C but yield decreased at elevated $CO_2$ with ambient +3.0 °C temperature. Therefore, it showed that elevated $CO_2$ is promoting the yield, but high temperature diminished growth and development of the crop plant.

There are various ways by which temperature impacts crop physiology and yields:

(I) Increasing temperature leads to a continuous elevation in the saturation vapor pressure of air, as a result of which the vapor pressure deficit (VPD) between air and the leaf becomes increased (VPD defined as the gap between the saturation vapor pressure and the actual vapor pressure of the air). Elevated VPD leads to a decrease in water use efficiency. However, plants transpire more water per unit of carbon assimilation (Willett et al. 2007). The plants reciprocate to enhance VPD by closing their stomata leading to reduced photosynthetic rates and consequently there is an increase in the temperature of the plant body. Hence, such warming effect may elevate the heat-related impacts on the plant body.

(II) High temperature can cause heat stress. It directly impairs the plant cells and their division, flowering, and fertilization period, which can lead to infertility, lower growth period, and yields (Teixeira et al. 2011).

(III) Or elevated temperature along with elevated $CO_2$, it may promote the growth, survival and spread of the various pathogen and their diseases particular to crops which lead to the loss of plant (Ziska et al. 2011).

## 5.5 Mitigation and Adaptation Strategies

Now, there is an urgent need for strategic considerations to adopt mitigation and adaptation measures. This measure could be a more operational, economical, and practical solution to the challenge of global warming and climate change. Under mitigation practices, the focus is on decreasing the concentration of anthropogenic greenhouse gases (GHGs) and the adaptation to climate change by developing various methods (Al-Ghussain 2018; Parry et al. 2007; Saxena and Sonwani 2020). Mitigation measures are those actions that are taken to decrease and control GHGs (abatement), while adaptation measures are based on reducing susceptibility to the effects of climate change (sequestration). Some mitigation measures should be followed to mitigate the increase of pollutant emissions such as the reduction in the use of fossil fuels, replacement by green energy sources, maximum use of renewable energy, electrification of industrial unit, well-organized transport system, i.e., electric public conveyance, bicycle, pooled cars, etc. On the other hand, an adaptation measure will be required to protect the source of revenue and food security in many developing and developed countries (IPCC 2001; Adger et al. 2003). However, Howden et al. (2007) proposed significant adaptation strategies in agriculture practices toward global warming and climate change:

1. To develop the resistant varieties and species to fight with heat stress and drought, inundating and salinization
2. Reassessing and altering fertilizer dose to retain grain yield or product as well as soil quality (Adams et al. 1990)
3. Changing the irrigation method and other water harvest management, i.e., drip irrigation
4. Managing the crop activities according to time and geographical location
5. Managing river water flows for more effective supply of water for irrigation and avoiding waterlogging, erosion, and nutrient loss
6. Crop diversification
7. To promote organic farming at selected sites
8. Proper application of integrated pest and pathogen management by emerging resistant varieties and species to pests and diseases
9. To promote the practice of knowledge of climate modelling and forecasting to reduce crop production risk
10. Increasing the income of farmer through mixed farming of fish with rice fields
11. Production of pasture land, altered pasture rotation, changing the time of grazing according to livestock stocking rates as well as altering the grazing times, modification and use of adapted forage crops according to livestock also
12. To introduce and promote forest conservation, agroforestry, and forest-based venture for extra income of agrarian peoples as well as restorating the degraded ecosystem

## 5.6 Summary

The emission of uncontrolled GHGs and other air pollutants due to industrialization and land use change pattern causes global warming and lead to climate change. Elevated $CO_2$ is the main causal factor for global warming by absorbing the infrared radiation and warm the earth atmosphere. This progressive warming of atmosphere causes global climate change. The elevated $CO_2$ and higher temperature interact with C3 and C4 crop and impact the growth and productivity of the plant via change in various physiological and biochemical processes. At current ambient $CO_2$ level, C3 plant will perform well whereas C4 plant is saturated somewhat and there is little change in photosynthetic rate. But at elevated $CO_2$ C3 plant get benefited up to some extent in initial period but after certain period plant faces N deficiency symptom due to hindrance of $NO_3$ assimilation. High temperature gives benefit to C4 plant as compared to C3 plant due to temperature-insensitive enzyme and do not have enzyme bi-functionality as well as anatomical specialization. The interaction of elevated $CO_2$ and higher temperature affect the crop yield, and quality may be increased or decreased depending on the geographical position of plants. It affects through various physiological processes such as photosynthesis, dark respiration, stomatal conductance, water use efficiency, transpiration process, and phenological process. Hence, decline of crop quality and productivity challenge the food security issue for the coming generation. Therefore, needs to develop the mitigation and adaptation strategies to curb the pollution level to ensure the sutainable development of society. Hence, the selection of crop is now an important concern according to environmental and geographical condition so that the plants are able to maintain and reduce the crop quality and yield loss.

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