Indian Journal of Weed Science (2024) **56**(4): 417–425
http://dx.doi.org/10.5958/0974-8164.2024.00063.7

REVIEW ARTICLE

Impact of climate change on soybean and associated weed interactions

Subhash Chander[1*], Dibakar Ghosh[2], Vikas C. Tyagi[3], Dasari Sreekanth[4], C.R. Chethan[4], Ravi Gowthami[1], Anju Mahendru Singh[1], Raghwendra Singh[5] and Kerur Vishwanath Raghavendra[6]

Received: 29 August 2024 | Revised: 7 November 2024 | Accepted: 9 November 2024

ABSTRACT

Soybean is an important oilseed crop, known to be fourth most cultivated crop globally, contributing to approximately 53% of total oil production. As a rainfed crop, soybean is particularly susceptible to the impacts of climate change. Climate change is expected to result in higher temperatures, elevated CO_2 levels and altered rainfall pattern. As per IPCC Synthesis Report 2023, climate change may increase global temperatures by 1.5°C between 2021 and 2040 under high-emission scenarios. Without substantial mitigation efforts, the consequences could be catastrophic, leading to a 3.6-4.4°C rise in global temperatures and CO_2 concentrations could rise to levels 2-4 times higher than those recorded in the past 0.8 million years, resulting in unprecedented climate changes. This climate change (elevated CO_2) is found to have a positive impact on soybean seed yield (increase 32-37%) under weed-free conditions, however, under weedy condition seed yield of soybean may be reduced by 30% by C_3 weeds and 45% by C_4 weeds. Thus, C_4 weeds are more competitive to C_3 crops such as soybean under climate change condition. Elevated temperature was found to have more direct and positive impact on growth of most of the weed species, while it negatively impacted the soybean growth and yield parameters. However, interaction effect of CO_2 and temperature was beneficial to both weeds and soybean. Apart from this, interaction of rainfall and temperature play a critical role in soybean productivity, where the simulation study advocates that increase in 1°C temperature with rainfall remaining constant, leads to a decline in productivity by 10-15%. Anticipating potential damage from weed to soybean is crucial for formulating effective and sustainable weed management strategies. Therefore, it is vital to address soybean-weed interactions and weed management in the context of climate change, as there has been inadequate research conducted in this area.

Keywords: Elevated CO_2, Crop-weed interaction, Elevated temperature, Emission, Rainfall, Soybean, Weed management

INTRODUCTION

Soybean (*Glycine max* L.) is an important oilseed and legume crop which possesses C_3 photosynthetic cycle. It is the fourth most cultivated crop globally, contributing to approximately 53% of total oil production (Beta and Isaak 2016). In India, the major weed flora of soybean is categorized into broad-leaf (*Commelina benghalensis, Eclipta prostrata*, *Phyllanthus niruri*, *etc*.), grasses (*Echinochloa colona, Ischaemum rugosum etc.*) and sedges (*Cyperus iria,* and *C. rotundus*) (Prachand *et al.* 2014, Patel *et al.* 2019, Dass *et al.* 2019, Chander *et al.* 2023a,b). These, weeds not only diminish the quality but also reduce the yields and also complicate the crop harvesting (Swinton *et al.* 1994, Boydston *et al.* 2008, Pawar *et al.* 2022). *E. colona* and *I. rugosum* are prominent weed species that lead to substantial yield losses and decline in the seed quality of soybean (Alarcon-Reverte *et al.* 2013). Yield reduction in soybean due to weeds can range from 33% to 100% (Billore *et al.* 1999), depending on weed type, intensity and the duration of competition with the crop. For instance, Oerke (2006) reported a global soybean production loss of 37% due to weed competition whereas Gharde *et al.* (2018) estimated that weeds cause losses of 1559 million USD in soybean in India.

There is a growing concern about soybean yield in India, as the current average stands at only 1.15 tons per hectare (Anonymous 2024), which is significantly lower than that of other major soybean-producing countries. As a rainfed crop, soybean is particularly vulnerable to the impacts of climatic

[1] Division of Germplasm Conservaton, ICAR-National Bureau of Plant Genetic Resources, New Delhi 110012, India

[2] ICAR-Indian Institute of Water Management, Bhubaneshwar, Odisha 751023, India

[3] ICAR-Indian Grassland and Fodder Research Institute, Jhansi, Uttar Pradesh 284003, India

[4] ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh 482004, India

[5] ICAR-Agricultural Technology Application Research Institute, Kanpur, Uttar Pradesh 208002 India

[6] ICAR-National Centre for Integrated Pest Management, New Delhi 110068, India

* Corresponding author: singhariya43@gmail.com

factors such as drought and extreme temperatures (Billy and Khanna 2018). These environmental stresses have become critical factors influencing food security by severely affecting crop productivity (Ribeiro *et al.* 2020). Climate change is expected to result in higher temperatures, elevated carbon dioxide (CO_2) levels, and rainfall is predicted to be erratic- in terms of amount, frequency, and intensity. These factors play a crucial role in the growth and development of plant species directly or indirectly affecting both crops (C_3 or C_4) and their competing weeds (C_3 or C_4) by affecting their vegetative growth, vigour and competitiveness (Raza *et al.* 2019; Sreekanth *et al.* 2024). Global warming defined as the continuous increase in the Earth's average temperature, is a primary driver of climate change (IPCC 2019). The rising temperatures impose significant constraints on crop growth and productivity, with high temperatures during key stages such as flowering and grain filling reducing yields and quality (Kaushal *et al.* 2016). As temperature extremes become more frequent and intense, particularly in tropical regions, the challenge of maintaining global food security grows more urgent (Sun *et al.* 2019). Also, global warming has already caused shifts in cultivation zones and contributed to the loss of genetic variability in crop species. This poses a direct threat to biodiversity and food security, leading to more unpredictable crop yields and ecosystem degradation (Khoury *et al.* 2014).

Understanding the relationship between climate change and agricultural productivity requires not only identifying temperature thresholds that threaten crop yields but also developing models that predict the impacts of extreme weather events, such as heat waves and droughts, on crop performance (Schauberger *et al.* 2021). Moreover, the combined effects of increased atmospheric CO_2 and higher temperatures on crop yields are complex. While elevated CO_2 can boost plant growth under certain conditions, its interaction with heat stress and water shortage often leads to diminished crop productivity (Degener 2015). Water availability is crucial to sustaining crop growth and any future scenarios of global warming must consider the shifts in irrigation and rainfed areas, particularly for key crops such as maize, wheat, rice, and soybean (Sloat *et al.* 2020). As temperatures continue to rise, and extreme weather events become more frequent, crop productivity is likely to decline. For example, for every 1°C increase in temperature, global maize yields decrease by 7.4%, wheat by 6.0%, rice by 6.2% and soybean by 3.1% (Parthasarathi *et al.* 2022). When combined with drought, these temperature increases result in even more substantial losses across cereal and non-cereal crops (Brás *et al.* 2021). As such, future agricultural practices must incorporate holistic strategies, including breeding for enhanced stress tolerance, to ensure food security in the face of ongoing climate change.

High temperatures negatively affect key physiological processes such as photosynthesis, transpiration, and respiration, ultimately leading to reduced yields in major food crops (Hatfield and Prueger 2015, Schauberger *et al.* 2017). The optimal temperature for soybean during its flowering and seed-filling stages is 30/22°C and deviations from this range can adversely affect plant growth and productivity (Thenveettil *et al.* 2024). The effect of increased temperature, CO_2 and their interaction on soybean and associated weeds (C_3 and C_4) have positive and negative impacts (Tungate *et al.* 2007, Chander *et al.* 2023). Rising CO_2 and temperatures may shift dominant weed species and aggravate weed problems (Ziska and Dukes 2011). An increase in CO_2 concentration has been shown to enhance net photosynthesis in C_3 plants, while C_4 plants exhibit a smaller response (Bowes 1996, Ghannoum *et al.* 2000). However, this generalization is not universal, as studies have reported differential responses among crops and weeds with the same photosynthetic pathways. For example, Ziska (2000) found that in a C_3 weed and C_3 crop interaction, the C_3 weed exhibited a greater overall response than the C_3 crop, resulting in reduced seed yield for soybean grown under elevated CO_2. Similarly, Patterson and Flint (1980) reported that increased atmospheric CO_2 might enhance the competitive impact of C_3 weeds in C_4 crops, while reducing the impact of C_4 weeds in C_3 crops.

Given the global importance of soybean, it is crucial to understand how climate change, particularly temperature and CO_2 will affect soybean productivity and behaviour of associated weeds. The goal of this review is to provide insights into the impact of climate change on soybean and its associated weed flora.

Current status of climate change: projections and potential impacts

The IPCC Synthesis Report-2023 underscores the growing challenges of climate change, noting the increasing probability that global temperatures could exceed 1.5°C between 2021 and 2040, particularly under high-emission scenarios (Bacchin *et al.* 2023 and IPCC 2023). Human-induced warming reached 1.31°C by 2023, driven by greenhouse gas emissions at record levels (Forster *et al.* 2024). Projections indicate that without significant mitigation efforts, CO_2 concentrations could reach levels two to four times higher than those observed in the last 0.8 million years, leading to unprecedented climatic changes (Raviraja 2023). According to the Intergovernmental Panel on Climate Change (IPCC), the global atmospheric CO_2 concentration to 730-1000 ìmol mol^{-1} by the end of the 21st century (Gianessi 2013, Varanasi *et al.* 2015). Further, if emissions remain unchecked, global temperatures could rise by 3.6 to 4.4°C by the end of the 21st century (Adak *et al.* 2023), with severe consequences for biodiversity, food security, water availability, agricultural or ecological drought *etc*. (**Figure 1**).

C_3 and C_4 plant physiology in relation to climate change

C_4 grasses are predicted to become more dominant in mid-latitude drylands due to increased climatic suitability, while C_3 grasses may decline in these regions (Anderson *et al.* 1993). In terms of weed physiology, C_3 weeds generally respond more positively to increased CO_2, which enhances their photosynthetic rates under optimal moisture conditions, potentially increasing their competitiveness against C_4 crops while C_4 weeds exhibit greater thermal tolerance, allowing them to thrive under elevated temperatures, which could expand their distribution range (Keerthi *et al.* 2023). Under elevated CO_2 in spite of enhanced photosynthesis in C_3 weeds, they may also encounter oxidative stress in high-temperature environments which may reduce their overall growth (Rakhmankulova *et al.* 2023) while, C_4 weeds biomass will be higher due to photosynthetic efficiency under elevated temperatures, even if they too face stress from combined climate factors (Rakhmankulova *et al.* 2023, Sendall *et al.* 2024). As climatic conditions evolve, these interactions will likely necessitate changes in weed management strategies.

C_3 and C_4 plants utilize different photosynthetic pathways that influence how they adapt to changing environmental conditions. C_3 crops, such as rice, wheat, and soybeans, tend to exhibit increased photosynthetic efficiency under elevated CO_2 levels, primarily due to reduced photorespiration and improved CO_2 assimilation (Drake *et al.* 1997). While elevated CO_2 can improve water-use efficiency and mitigate some of the effects of drought in C_3 crops, C_4 crops may experience less benefit due to their naturally high water-use efficiency under normal

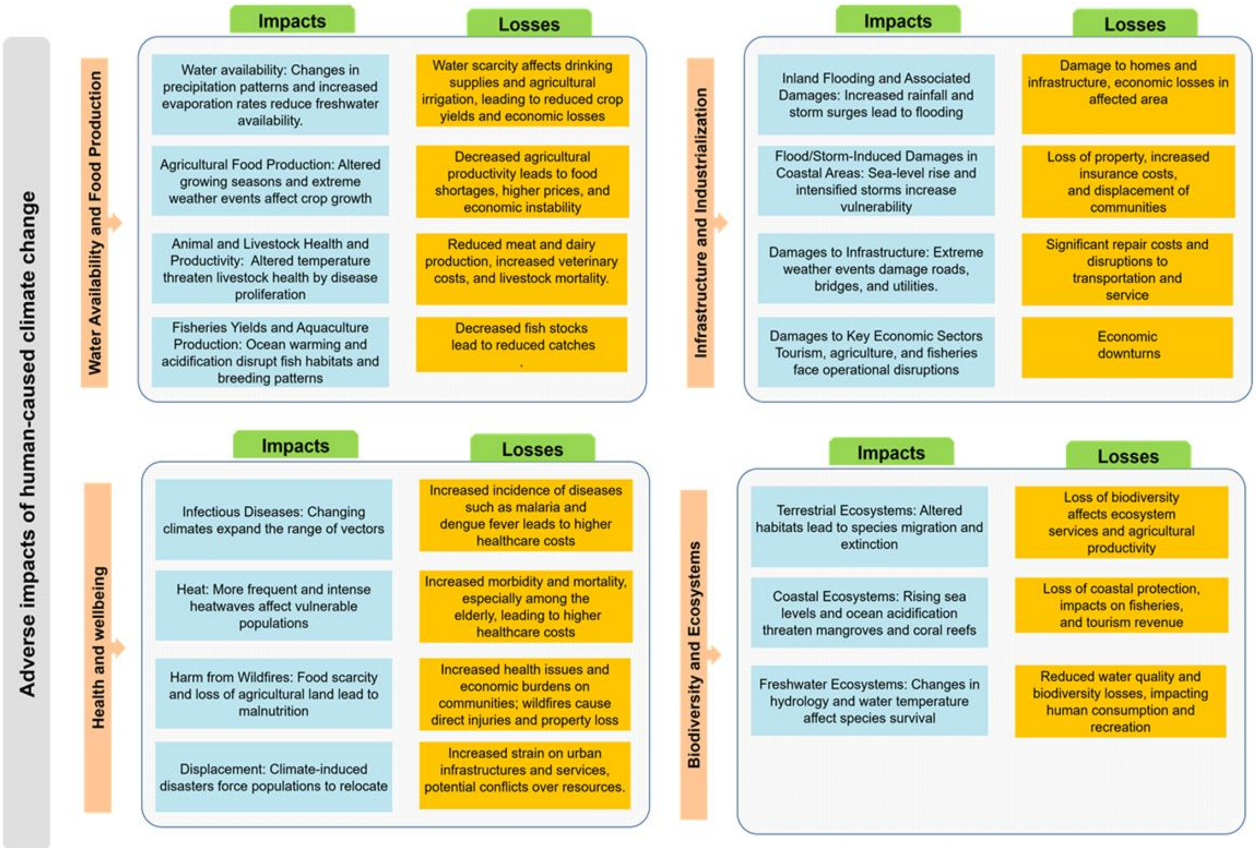

Figure 1. Impact and losses by climate change caused by anthropogenic activity

conditions (Leakey *et al.* 2019, van der Kooi *et al.* 2016). Moreover, elevated CO_2 may worsen drought sensitivity in C_4 plants by increasing leaf area, which can raise water demand (Burkart *et al.* 2011). Given the complexity of these responses, predicting how C_3 and C_4 crops will fare under future climate conditions remains challenging.

Impact of elevated CO_2 on soybean and associated weeds

Weeds and crops may react differently to CO_2 enrichment due to interactions between CO_2 enrichment and other environmental parameters like temperature, availability of water and nutrients and so on (Patterson and Flint 1980, Zangerl and Bazzaz 1984, Naidu 2015, Naidu and Murthy 2014). The photosynthetic pathway is an important consideration, especially because many of the world's most troublesome weeds are C_4 plants, which tend to photosynthesize more effectively at higher temperatures and, as a result, are probably better able to utilize higher CO_2 levels than C_3 plants, which include crops (Alberto *et al.* 1996). Increasing CO_2 concentrations would benefit C_3 crops such as rice, wheat, and soybeans, making them more competitive than C_4 weeds. However, when both crops and weeds share the same photosynthetic pathway, weed growth has been found to improve when CO_2 levels rise. Ziska noted that when *Abutilon theophrasti* and soybean were grown in competition with each other at greater CO_2 levels, the competition benefited the soybeans, as seen by higher pod numbers/plant (Ziska 2013). However, when another ubiquitous plant, *Chenopodium album*, was cultivated in a Canadian grassland environment, CO_2 enrichment failed to induce higher growth in *C. album* (Taylor and Potvin 1997).

Lal *et al.* (1999) have found that soybean yield increased by 50% when doubling CO_2 level based on the CROPGRO simulation model. In one study, it was shown that, when CO_2 concentration was doubled, the total biomass production was increased by 40% with no changes in the C/N ratio whereas nitrogen content was improved (29%) due to enhanced atmospheric nitrogen fixation in soybean (Torbert *et al.* 2004). This study directed that although biomass and nitrogen content were increased, there was no need to change (increase or decrease) the fertilization application in soybean. In a different study, Ziska (2000) examined the impact of competition between 'Round-up Ready' soybean and a C_3 weed (*C. album*) and a C_4 weed (*Amaranthus retroflexus*), cultivated under both ambient and elevated CO_2 levels (ambient+250 ppm). Under weed-free conditions, increased CO_2 levels led to increased soybean growth and yield compared to ambient CO_2 conditions. However, both weed species significantly decreased soybean growth and yield at all CO_2 levels. At high CO_2, *C. album* caused a 28 to 39% drop in soybean seed production compared to the weed-free control. Similarly, the dry weight of *C. album* rose by 65%. Conversely, with *A. retroflexus*, soybean seed yield losses decreased from 45 to 30% as CO_2 levels increased, although weed dry weight remained constant. This study implies that rising CO_2 levels may modify yield losses caused by weed competition, and that weed control will be critical in realizing any possible rise in soybean crop yield, when climate change happens. It appears that the crop would profit from higher CO_2 only when the weed is C_4 and the crop is C_3, but in all other circumstances, weeds are projected to outsmart crop in a crop-weed competition situation. Thus, while rising CO_2 levels definitely boost weed development in general, weed-crop competition connections should be assessed on an individual basis. In another study, Santos *et al.* (2017) discovered that the projected increases in atmospheric CO_2 levels should not affect these traits, after atmospheric CO_2 concentrations reach 800 ppm, *Euphorbia heterophylla* being more aggressive than soybeans. However, it has been discovered that increasing CO_2 levels in the environment increases the aggressiveness of soybean cultivation in comparison to *E. heterophylla*. Chander *et al.* (2023) have revealed that elevated CO_2 (550 ppm) has positive impact on root nodules (32.17%), plant height (13%), plant dry weight (13.42%), number of pods per plant (7.88%), yield (36.61%) of soybean under weed-free conditions, whereas very little increment was observed in the presence of weeds. Elevated CO_2 also had positive impact on plant height (25.73%; 40.79%), plant dry weight (62.63%; 16.21%) and number of tillers/plant (85.92%; 56.76%) of two weed species *E. colona* and *I. rugosum*, respectively, hence yield of soybean infested with these two weed species at elevated CO_2 was decreased by 31.12%. Lenka *et al.* (2017) reported that at elevated CO_2 (550 ppm), the leaf area, biomass at harvest and grain yield were significantly improved by 143%, 47% and 51%, respectively, in soybean over ambient conditions.

Morgan *et al.* (2005) reported that when soybean was grown in Free-Air Carbon Dioxide Enrichment (FACE) facility (550 ppm CO_2), there was increase in net primary production *i.e.* biomass (17-18%) and yield (15%), but it was less than the previous open-top chamber experiment. Similarly, Davis and Ainsworth (2012), demonstrated that in FACE experiment soybean plant height was slightly higher in weedy (9%) and weed free (11%) condition in elevated CO_2 (550 ppm). They point out that the proportion of soybean yield was greater in weedy condition compared to weed-free condition at elevated CO_2, it may be due to the interference being moderated by increased CO_2 and more reduction in interference was found in *Amaranthus rudis* (37%) than *C. album* (11%). Thus, study implies that C_4 weed (*A. rudis*) has non signification interference, whereas C_3 weed has greater interference with significant difference due to photosynthetic advantage at elevated CO_2. They also suggested that C_3 and C_4 weed communities were equally likely to dominate at ambient CO_2 condition whereas greater chance of C_3 weed community (90% chance) to dominate under elevated CO_2 condition. Based on the 30-year (1980-2010) climatic data, Mohanty *et al.* (2017) suggested that with increase in CO_2 concentration (750 ppm) soybean yield was increased (30%).

Impact of elevated temperature on soybean and associated weeds

It is predicted that the global earth's surface temperature will upsurge by 1.5-4.0°C, which is correlated with doubling CO_2 concentration and greenhouse effect over 21st century (IPCC 2023). This increased temperature will lead to water stress and subsequently plant growth will suffer due to evapo-transpiration (Billore 2019). Plants with the C_4 photosynthetic pathway, which are predominant weeds, will have a competitive edge over staple food crops, *viz*. rice, wheat, soybean etc., which are primarily C_3, under high temperatures. Hence, its crucial to understand how soybean and associated weeds will behave under increased temperature.

Chander *et al*. (2023) found that with rise in temperature of 2°C, the plant height, plant dry weight, number of pods/plant and yield of soybean were reduced by 6.25%, 19.44%, 26.67% and 5.48% respectively in weed free condition compared to ambient condition in open top chamber. In contrast when soybean grown with two weeds (*E. colona* and *I. rugosum*), the plant height, plant dry weight, number of pods/plant and yield was decreased by 49.47%, 47.80%, 95.42% and 56.40% respectively. It happened due to enhanced impact of elevated temperature on the growth (plant height, plant dry weight and the number of tillers) of *E. colona* and *I. rugosum* (**Table 1**). Similarly, Lenka *et al*. (2017) observed that with increase in temperature of 2°C, the leaf area, biomass at harvest and grain yield were increased by 281%, 31% and 30%, respectively in soybean. Seed index (100 seed weight) of soybean was significantly increased at elevated temperature. Chen *et al*. (2013) used the climate data of temperature, radiation and rainfall from 820 weather stations and production data from 2001-2009 in China and simulated that reduction in soybean yield (5-10% and 8-22%) was more prominent than corn in slow warming scenario (2-5%) and fast warming scenario (5-15%), respectively. In another study of simulation of climatic and production data of soybean (1980-2010), it is indicated that with 10% increase in temperature along with low rainfall, the soybean yield was reduced by 10% (Mohanty *et al*. 2017). They predicted that declining the temperature by 1°C (from the base) and increasing the rainfall (>10%) encouraged the soybean productivity, however with rise in temperature by 1°C with constant rainfall led to decline in soybean productivity (10-15%). In their study, Tungate *et al*. (2007) examined how temperature affected *Sida spinosa*, *Cassia obustutifolia*, and soybean. They found that while all species showed an upward tendency in root: shoot ratios as temperatures rose, weeds consistently exhibited higher ratios. When growth was at its highest, the root: shoot growth ratio for soybean (at 32/27°C) was 0.8, while for *S. spinosa* (at 36/31°C) and *C. obustutifolia* (at 36/31°C), it was 1.3 and 1.6, respectively. Tremmel and Patterson (1993) also studied the variation in diurnal temperature (high: 28/22, 30/23, 31/24 and 32/26°C; ambient: 24/18, 26/19, 27/20 and 28/22°C) and elevated CO_2 (700 ppm) on soybean and associated weeds, *viz*. *Sorghum halepense*, *Elytiga repens*, *Amaranthus retroflesus*, *Cassia obtusifloia* and *Abutilon theophrasti*. They noted that the growth responses of these species to temperature were more clear-cut than their reactions to CO_2. Leaf area and biomass were significantly lower at high temperature than ambient in *E. repens*, however, contrasting results were observed for other species for plant height and leaf area with greater significance.

Impact of elevated CO_2 and their interaction with temperature and rainfall on soybean and associated weeds

Research conducted in Central India using open-top chambers, Chander *et al*. (2023) found an increase in biomass of soybean (7.62%), *I. rugosum* (27.83) and *E. colona* (9.65%) under the combination of elevated temperature and CO_2 (**Table 1**). The increased biomass may be due to the higher rate of carboxylation and reduced rate of photorespiration (Bhattacharyya and Roy 2013). Chander *et al*. (2023) also reported that the combination of elevated CO_2 and temperature has positive impact on seed yield (7.6% increase) and number of pods/plant (4.24%), this may be due to the greater ability to fix atmospheric nitrogen in presence of root nodules (Hikosaka *et al.* 2011). Future research on C_3 and C_4 crop-weed competition under changing climatic circumstances is vital, as the current study's findings suggest that C_4 weeds may become more competitive with C_3 crops. Lenka *et al.* (2017) found that elevated CO_2 and temperature significantly increased leaf area (259%), biomass at harvest (47%) and grain yield (65%) compared to elevated CO_2 alone. Heinemann *et al.* (2006) studied the effect of diurnal variation of temperature (20/15, 25/20 and 30/25°C) and elevated CO_2 (700 ppm) on growth and development of soybean. They found that soybean flowered two days early at 25/20°C and elevated CO_2 condition compared to ambient condition, however no change in flowering was observed in other temperature and CO_2 combination. This early flowering seemed to be owing to the strong effect of temperature than elevated CO_2 (Sionit *et al.* 1987a,b, Baker *et al.* 1989). They advocated that the biomass growth rate was higher at low temperature (20/15°C) and elevated CO_2, which was also supported by Sionit *et al.* (1987b). In contrast, at higher temperature regime (30/25°C), the biomass growth rate was higher at ambient situation than increased CO_2 condition, due to the soybean's reduced response to increased CO_2 over time because of biochemical limitations (Pritchard *et al.* 1999). Seed weight was improved at 20/15 and 30/35°C temperature regime by 7.5% under increased CO_2, though the improvement was smaller at higher temperature regime (Heinemann *et al.* 2006). Tremmel and Patterson (1993) found that biomass was significantly higher in soybean and all the weeds except *S. halepense* at elevated CO_2 and ambient (26/19°C) or high temperature (30/23°C). Elevated CO_2 and temperature (30/23°C) had a much greater positive impact on biomass than leaf area at early harvest, with substantial overall response, but no visible impact of CO_2 at later harvest stage was observed. At early harvest stage, *S. halepense* had no noticeable impact of elevated CO_2, however at later harvest leaf area was greater at elevated CO_2 and high temperature (30/23°C), indicating significant interaction of CO_2 and temperature. In *C. obtusifolia* the significant interaction of CO_2 and temperature

Table 1. Impact of elevated CO_2 (EC), elevated temperature (ET) and combination (EC+ET) on soybean and associated weeds compared to ambient condition

Crop/weed species	Trait	CO_2 level (ppm)	Elevated temperature (°C)	Percent increase (+)/decrease (-)			Reference
				EC	ET	EC+ET	
Glycine max	Yield	660	-	+50	-	-	Lal *et al.* 1999
Glycine max	Total biomass production	730	-	+40	-	-	Torbert *et al.* 2004
Glycine max	C/N ratio	730	-	+29	-	-	Torbert *et al.* 2004
Glycine max	Leaf area	550	2	+143	+281	+259	Lenka *et al.* 2017
Glycine max	Biomass at harvest	550	2	+47	+31	+47	Lenka *et al.* 2017
Glycine max	Grain yield	550	2	+51	+30	+65	Lenka *et al.* 2017
Glycine max (Amaranthus retroflexus)	Biomass	Ambient	-	-36	-	-	Ziska 2000
Glycine max (Chenopodium album)	Biomass	Ambient	-	-23	-	-	Ziska 2000
Glycine max (weed-free)	Biomass	Ambient+ 250	-	+32	-	-	Ziska 2000
Glycine max (Amaranthus retroflexus)	Seed yield	Ambient	-	-45			Ziska 2000
Glycine max (Chenopodium album)	Seed yield	Ambient	-	-28			Ziska 2000
Glycine max (Amaranthus retroflexus)	Seed yield	Ambient+ 250	-	-30	-	-	Ziska 2000
Glycine max (Chenopodium album)	Seed yield	Ambient+ 250	-	-39	-	-	Ziska 2000
Glycine max	Productivity	-	1	-	+10-15	-	Mohanty *et al.* 2017
Glycine max (weed-free)	Biomass	550±50	2	+13.4	-	+7.62	Chander *et al.* 2023
Glycine max (weed-free)	Root nodules	550±50	2	+32	-25	-	Chander *et al.* 2023
Glycine max (weed-free)	Plant height	550±50	2	+13	-6.25	+6.73	Chander *et al.* 2023
Glycine max (weed condition)	Plant height	550±50	2	+3.4	-49.5	-6.01	Chander *et al.* 2023
Glycine max (weed-free)	Dry weight	550±50	2	+13.4	-19.4	+7.62	Chander *et al.* 2023
Glycine max (weed condition)	Dry weight	550±50	2	-16.4	-47.8	-18.7	Chander *et al.* 2023
Glycine max (weed-free)	Pods/plant	550±50	2	+7.88	-26.7	+4.24	Chander *et al.* 2023
Glycine max (weed condition)	Pods/plant	550±50	2	-42.4	-95.4	-49.7	Chander *et al.* 2023
Glycine max (weed-free)	Seed yield	550±50	2	+37.6	-5.48	+7.16	Chander *et al.* 2023
Glycine max (weed condition)	Seed yield	550±50	2	-31.1	-56.4	-33.4	Chander *et al.* 2023
Echinochloa colona	Plant height	550±50	2	+25.7	+10.79	+28.2	Chander *et al.* 2023
Echinochloa colona	Dry weight	550±50	2	+62.6	+64.9	+9.65	Chander *et al.* 2023
Echinochloa colona	No of tillers/plant	550±50	2	+85.9	+146	+33.8	Chander *et al.* 2023
Echinochloa colona	Biomass	550±50	2	+62.6	+64.9	+9.65	Chander *et al.* 2023
Ischemum rugosum	Plant height	550±50	2	+40.5	+26.4	+32.9	Chander *et al.* 2023
Ischemum rugosum	Dry weight	550±50	2	+16.2	+37.2	+27.8	Chander *et al.* 2023
Ischemum rugosum	No of tillers/plant	550±50	2	+56.7	+89.2	+24.3	Chander *et al.* 2023
Ischemum rugosum	Biomass	550±50	2	+16.2	+37.2	+27.8	Chander *et al.* 2023

was observed for biomass, though no impact was observed in leaf area. Conversely, in *A. theophrasti*, a negative impact of CO_2 and temperature interaction was observed for leaf area.

Conclusion

The studies on the impact of climate change on soybean and its associated weeds are limited. However, the available studies have confirmed that both soybean and its associated weeds respond differently to climate change. Weeds typically supersede over soybean due to their superior adaptation and positive effect of climate change. Additionally, weeds show intraspecific variation and physiological plasticity due to which they also have competitive advantage over soybean. Both elevated CO_2 and temperature, have encouraging impact on growth parameters of C_3 and C_4 weeds, however, C_4 weeds causing less interference with soybean than the C_3 weeds. Also, elevated CO_2 has positive impact on soybean but is negatively impacted by elevated temperature. In addition to this, elevated CO_2 was found to have a positive impact on soybean seed yield (increase 32-37%) under weed free condition. However, under weedy condition seed yield of soybean may be reduced by 30% by C_3 weeds and 45% by C_4 weeds. Studies have also shown that, elevated CO_2 and temperature interacted positively, benefiting both soybean and weed species. One simulation study suggests that, 10% increase in temperature combined with low rainfall can reduce soybean yield by 10%. Conversely, a decrease in temperature by 1°C and an increase in rainfall of more than 10% can enhance soybean productivity. Thus, it indicates the critical interplay between temperature and rainfall in determining soybean yields and underscores the need for adaptive management strategies in response to changing climatic conditions. Anticipating potential damage from weed to soybean crop is essential for implementing sustainable weed management strategies. Hence, more studies are required to understand and, simulate soybean-weed interaction and develop weed management approaches in climate change scenario.

REFERENCES

Adak S, Mandal NA, Mukhopadhyay A, Maity PP and Sen S. (2023). "Current state and prediction of future global climate change and variability in terms of CO_2 levels and temperature, pp. 15–43. In: *Enhancing Resilience of Dryland Agriculture Under Changing Climate: Interdisciplinary and Convergence Approaches*, Singapore: Springer Nature Singapore.

Alarcon–Reverte R, Garcia A, Urzua J and Fisher AJ. 2013. Resistance to glyphosate in junglerice (*Echinochloa colona*) from California. *Weed Science* **61**: 48–54.

Alberto AMP, Ziska LH, Cervancia CR and Manalo PA. 1996. The influence of increasing carbon dioxide and temperature on competitive interactions between a C_3 crop, rice (*Oryza sativa*) and a C_4 weed (*Echinochloa glabrescens*). *Australian Journal of Plant Physiology* **23**: 795–802.

Anderson DM, Swanton CJ, Hall JC and Mersey BG. 1993. The influence of temperature and relative humidity on the efficacy of glufosinate–ammonium. *Weed Research* **33**: 139–147.

Anonymous. 2024. ICAR–Indian Institute of Soybean Research. Statistics Retrieved on 20 September 2024 from https://iisrindore.icar.gov.in/statistics.html.

Bacchin TK, Hooimeijer F and Kothuis BL. 2023. Prospects. *Journal of Delta Urbanism* **4**: 4–10.

Baker JT, Allen Jr LH, Boote KJ, Jones P and Jones JW. 1989. Response of soybean to air temperature and carbon dioxide concentration. *Crop Science* **29**(1): 98–105.

Beta T and Isaak C. 2016. Grains around the world. *Encyclopedia of Food Grains* pp 349–428.

Bhattacharyya P and Roy KS. 2013. Influence of elevated carbon dioxide and temperature on belowground carbon allocation and enzyme activities in tropical flooded soil planted with rice. *Environmental Monitoring and Assessment* **185**: 8659–8671.

Billore SD, Joshi OP and Ramesh A. 1999. Energy productivity through herbicidal weed control in soybean. *Indian Journal of Agricultural Sciences* **69**(11): 770–772.

Billore SD. 2019. Weeds in Soybean visa–vis other crops under climate change–A Review. *Soybean Research* **17**: 01–21.

Billy C and Khanna VK. 2018. Impact of climate change in Indian agriculture special emphasis to soybean *Glycine Max* L. Merr. *Open Access Journal of Oncology* **2**(4): 141.

Bowes G. 1996. Photosynthetic responses to changing atmospheric carbon dioxide concentration, pp. 397–407. In: *Photosynthesis and the environment* (Ed. Baker NR), Kluwer, Dordrecht.

Boydston RA, Mojtahedi H, Crosslin JM, Brown CR and Anderson T. 2008. Effect of hairy night shade (*Solanum sarrachoides*) presence on potato nematodes, diseases, and insect pests. *Weed Science* **56**: 151–154.

Brás T, Seixas J, Carvalhais N, Jägermeyr J. 2021. Severity of drought and heatwave crop yield losses are amplified by climate change and vary strongly among crop types and regions. *Proceedings of the National Academy of Sciences USA* **118**(9): e2114741118.

Burkart S, Manderscheid R and Weigel HJ. 2011. Interactive effects of elevated CO_2 and drought stress on photosynthesis and water relations of perennial ryegrass. *Journal of Agronomy and Crop Science* **197**(3): 195–207.

Chander S, Ghosh D, Pawar D, Sreekanth D, Chethan CR and Singh PK. 2023a. Elevated CO_2 and temperature influence on crop–weed interaction in soybean. *Indian Journal of Weed Science* **55**(3): 287–293.

Chander S, Ghosh D, Tyagi VC, Chethan CR, Pawar D, Gharde Y, Kumar B, Singh PK. 2023b. Imazethapyr-Resistant Jungle Rice (*Echinochloa colona*) in Soybean Growing Belt of Central India: A Case Study. *Agricultural Research* **12**(3): 298–307.

Chen S, Chen X and Xu J. 2013. Impacts of climate change on corn and soybean yields in China, pp 1–46. In: *Agricultural* and *Applied Economics Association's Joint Annual meeting*. Washington DC.

Dass A, Dey D, Lal SK and Rajanna GA. 2019. Tank–mix insecticide and herbicide application effects on weeds, insect pest menace and soybean productivity in semi–arid northern plains of India. *Legume Research* **42**(3): 385–91.

Davis AS and Ainsworth EA. 2012. Weed interference with field grown soyabean decreases under elevated CO_2 in a FACE experiment. *Weed Research* **52**(3): 277–285.

Degener JF. 2015. The fertilization effect of elevated CO_2 in the context of heat stress. *Journal of Plant Physiology* **172**: 180–189.

Drake BG, Gonzalez–Meler MA and Long SP. 1997. More efficient plants: A consequence of rising atmospheric CO_2? *Annual Review of Plant Biology* **48:** 609–639.

Forster Piers M, Chris Smith, Tristram Walsh, William F Lamb, Robin Lamboll, Bradley Hall, Mathias Hauser, et al. 2024. Indicators of Global Climate Change 2023. annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data* **16**(6): 2625–2658.

Ghannoum O, Caemmerer SV, Ziska LH and Conroy JP. 2000. The growth response of C_4 plants to rising atmospheric CO_2 partial pressure a reassessment. *Plant, Cell* and *Environment* **23**(9): 931–942.

Gharde Y, Singh PK, Dubey RP and Gupta PK. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107**: 12–8.

Gianessi LP. 2013. The increasing importance of herbicides in worldwide crop production. *Pest Management Science* **69**: 1099–1105.

Hatfield JL and Prueger JH 2015. Temperature extremes Effect on plant growth and development. *Weather and Climate Extremes* **10**: 4–10.

Heinemann AB, de HN Maia A, Dourado–Neto D, Ingram KT and Hoogenboom G. 2006. Soybean *Glycine max* L.Merr growth and development response to CO_2 enrichment under different temperature regimes. *European Journal of Agronomy* **24**(1): 52–61.

Hikosaka K, Kinugasa T, Oikawa S, Onoda Y, Hirose T. 2011. Effects of elevated CO_2 concentration on seed production in C_3 annual plants. *Journal of Experimental Botany* **62**(4): 1523–1530.

IPCC 2019. Climate Change and Land an IPCC Special Report on Climate Change Desertification Land Degradation Sustainable Land Management Food Security and Greenhouse Gas Fluxes in Terrestrial Ecosystems.

IPCC 2023. Climate Change 2023: Synthesis Report, pp 184. In: *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds. Core Writing Team, Lee H and Romero J), IPCC, Geneva, Switzerland.

Kaushal N, Bhandari K, Siddique KH, Nayyar H. 2016. Heat stress in food legumes Effects tolerance mechanisms and management strategies. *Plant Physiology and Biochemistry* **96**: 409–418.

Keerthi MM, Sharmili KS, Arun A, Govindhasamy R. 2023. Emerging Weed Problems under Changing Climatic Condition: A Review. *International Journal of Enviornment and Climate Change* **13**(7): 559–574.

Khoury CK, Bjorkman AD, Dempewolf H, *et al*. 2014. Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences USA* **111**(11): 4001–4006.

Lal M, Singh KK, Srinivasan G, Rathore LS, Naidu D and Tripathi CN. 1999. Growth and yield responses of soybean in Madhya Pradesh, India to climate variability and change. *Agricultural and Forest Meteorology* **93**(1): 53–70.

Leakey ADB, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP and Ort DR. 2019. Elevated CO_2 effects on plant carbon, nitrogen, and water relations Six important lessons from FACE. *Journal of Experimental Botany* **70**(9): 2849–2856.

Lenka NK, Lenka S, Thakur JK, Elanchezhian R, Aher SB, Simaiya V, Yashona DS, Biswas AK, Agrawal PK and Patra AK. 2017. Interactive effect of elevated carbon dioxide and elevated temperature on growth and yield of soybean. *Current Science* **113**(12): 2305–2310.

Mohanty M, Sinha NK, McDermid SP, Chaudhary RS, Reddy KS, Hati KM, Somasundaram J, Lenka S, Patidar RK, Prabhakar M and Cherukumalli SR. 2017. Climate change impacts vis–à–vis productivity of soybean in vertisol of Madhya Pradesh. *Journal of Agrometeorology* **19**(1): 10–16.

Morgan PB, Bollero GA, Nelson RL, Dohleman FG and Long SP. 2005. Smaller than predicted increase in aboveground net primary production and yield of field grown soybean under fully open air [CO_2] elevation. *Global Change Biology* **11**(10): 1856–65.

Naidu VS and Murthy TG. 2014. Crop–weed interactions under climate change. *Indian Journal of Weed Science* **46**(1): 61–65.

Naidu VS. 2015. Climate change, crop–weed balance and the future of weed management. *Indian Journal of Weed Science* **47**(3): 288–295.

Oerke EC. 2006. Crop losses to pests. *Journal of Agricultural Science* **144**: 31–43.

Parthasarathi T, Srinivasan P and Arulbalachandran D. 2022. Impact of global warming on crop yield A meta–analysis. *Agricultural Systems* **194**: 103279.

Patel A, Spare N and Malgaya G. 2019. Bio–efficacy of post emergence herbicides against weed control in soybean. *International Journal of Current Microbiology and Applied Sciences* **8**(4): 1964–1974.

Patterson DT and Flint EP. 1980. Potential effects of global atmospheric CO_2 enrichment on the growth and competitiveness of C_3 and C_4 crop plants. *Weed Science* **28**: 71–75.

Pawar D, Sreekanth D, Chander S, Chethan CR, Sondhia S, Singh PK. 2022. Effect of weed interference on rice yield under elevated CO_2 and temperature. *Indian Journal of Weed Science* **54**(2): 129–136.

Prachand S, Kubde KJ and Bankar S. 2014. Effect of chemical weed control on weed parameters growth yield attributes yield and economics in soybean *Glycine max*. *American–Eurasian Journal of Agricultural and Environmental Sciences* **14**(8): 698–701.

Pritchard SG, Rogers HH, Prior SA, Peterson CM. 1999. Elevated CO_2 and plant structure: a review. *Global Change Biology* **5**: 807–837.

Rakhmankulova ZF, Khamidullina MA, Sokolova AG and Akhmatov KA. 2023. Complex effects of climate change on photosynthetic processes and productivity of C_3 and C_4 plants. *Russian Journal of Plant Physiology* **70**(2): 158–170.

Raviraja S. 2023. Future climate change. *GSC Advanced Research and Reviews* **14**(01): 50–54.

Raza A, Razzaq A, Mehmood S, Zou X, Zhang X and Lv Y. 2019. Impact of climate change on crops adaptation and strategies to tackle its outcome *a review. Plants Basel* **8**: 34.

Ribeiro FN, Fernandes TJ, Teixeira CI *et al.* 2020. High temperature–induced changes in phenolic compounds in crops. *Journal of Experimental Botany* **71**(12): 3787–3796.

Santos JI, Cesarin AE, Sales CAR, Triano MBB, Martins PFRB, Braga AF, Neto NJ, Barroso AAM, Alves PLCA and Huaman CAM. 2017. Increase of atmosphere CO_2 Concentration and its effects on culture weed interaction. *International Journal of Agricultural and Biosystems Engineering* **11**(6): 419–426.

Schauberger B, Archontoulis S, Arneth A, Balkovic J, Ciais P, Deryng D et al. 2017. Consistent negative response of US crops to high temperatures in observations and crop models. *Nature Communications* **8**(1): 1–9.

Schauberger B, Ben AT, Makowski D, *et al.* 2021. Temperature effects on crop yields in extreme heat environments. *Environmental Research Letters* **16**: 015001.

Sendall KM, Muñoz CM, Ritter AD, Rich RL, Noyce GL and Megonigal JP. 2024. Effects of warming and elevated CO_2 on stomatal conductance and chlorophyll fluorescence of C_3 and C_4 coastal wetland species. *Wetlands* **44**(4): 43.

Sionit N, Strain BR and Flint EP. 1987a. Interaction of temperature and CO_2 enrichment on soybean: growth and dry matter partitioning. *Canadian Journal of Plant Science* **67**: 59–67.

Sionit N, Strain BR and Flint EP. 1987b. Interaction of temperature and CO_2 enrichment on soybean: photosynthesis and seed yield. *Canadian Journal of Plant Science* **67**: 629–636.

Sloat LL, Davis SJ, Gerber JS, *et al.* 2020. Climate change is shortening the growing season and reducing maize yield in major producing regions. *Environmental Research Letters* **15**: 084001.

Sreekanth D, Pawar DV, Kumar R, Ratnakumar P, Sondhia S, Singh PK, Mishra JS, Chander S, Mukkamula N, Kiran Kumar B. 2024. Biochemical and physiological responses of rice as influenced by *Alternanthera paronychioides* and *Echinochloa colona* under drought stress. *Plant Growth Regulation* **103**(1): 119–137.

Sun Y, Gu L, Dickinson RE, *et al.* 2019. Heat stress in global agriculture under climate change. *Global Change Biology* **25**(4): 1342–1359.

Swinton SM, Buhler DD, Forecella F, Gunsolus JL and King RP. 1994. Estimation of crop yield loss due to interference by multiple weed species. *Weed Science* **42**: 103–109.

Taylor K and Potvin C. 1997. Understanding the long–term effect of CO_2 enrichment on a pasture the importance of disturbance. *Canadian Journal of Botany* **75**: 1621–1627.

Thenveettil N, Bheemanahalli R, Reddy KN, Gao W and Reddy KR. 2024. Temperature and elevated CO_2 alter soybean seed yield and quality exhibiting transgenerational effects on seedling emergence and vigor. *Frontiers in Plant Science* **15**: 1427086.

Torbert HA, Prior SA, Rogers HH and Runion GB. 2004. Elevated atmospheric CO_2 effects on N fertilization in grain sorghum and soybean. *Field Crops Research* **88**(1): 57–67.

Tremmel DC and Patterson DT. 1993. Responses of soybean and five weeds to CO_2 enrichment under two temperature regimes. *Canadian Journal of Plant Science* **73**(4): 1249–1260.

Tungate KD, Israel DW, Watson DM and Rufty TW. 2007. Potential changes in weed competitiveness in an agroecological system with elevated temperatures. *Environmental and Experimental Botany* **60**(1): 42–49.

van der Kooi CJ, Reich M, Löw M and De Kok LJ. 2016. Growth and yield of C_3 and C_4 crops under different atmospheric CO_2 concentrations and their response to drought stress. *Acta Physiologiae Plantarum* **38**(3): 1–9.

Vanaja M, Sarkar B, Sathish P, Jyothi Lakshmi N, Yadav SK, Mohan C, Sushma A et al. 2024. Elevated CO_2 ameliorates the high temperature stress effects on physio–biochemical growth yield traits of maize hybrids. *Scientific Reports* **14**(1): 2928.

Varanasi A, Prasad PVV and Jugulam M. 2015. Impact of climate change factors on weeds and herbicide efficacy. *Advances in Agronomy* **135**: 107–146.

Zangerl AR and Bazzaz FA. 1984. The response of the plants to elevated CO_2. *Oecologia* **62**: 196–198.

Ziska L. 2013. Observed changes in soybean growth and seed yield from *Abutilon theophrasti* competition as a function of carbon dioxide concentration. *Weed Research* **53**:140–145.

Ziska LH and Dukes JS. 2011. Weed Biology and Climate Change, pp 68–205. Ames IA Blackwell Publishing Ltd.

Ziska LH. 2000. The impact of elevated CO_2 on yield loss from a C_3 and C_4 weed in field grown soybean. *Global Change Biology* **6**(8): 899–905.