Interactive effect of elevated carbon dioxide and elevated temperature on growth and yield of soybean

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A field experiment was undertaken in the *kharif* season of 2016 in open-top chambers to study the individual and combined effects of elevated carbon dioxide and temperature on growth and yield parameters in soybean crop. The soybean (var. JS 20–29) crop was grown under two levels of CO_2 (ambient, 550 ppmv) in combination with two levels of air temperature (ambient, +2.0°C). The five different climate treatments were: open field (OF), ambient chamber (AC), elevated temperature (eT), elevated CO_2 (eC) and elevation of both temperature and CO_2 (eCeT). At the time of sowing, vermicompost @ 2.0 tonnes ha^{-1} was applied along with 30 kg N ha^{-1} (in the form of urea), 60 kg P_2O_5 ha^{-1} (through single super phosphate) and 40 kg K_2O ha^{-1} (through muriate of potash) to the soybean crop. Impact of the climate variables was studied in terms of selected plant attributes, viz. plant height, leaf area, biomass, number of pods, number of grains per pod, grain yield and seed index (100 seed weight). Results indicated significant positive effect of elevated CO_2 and temperature on plant growth parameters, pod attributes and grain yield. Compared to AC, leaf area at 50 days after sowing was higher by 143%, 281% and 259% and above-ground biomass at harvest was higher by 47%, 31% and 47% under eC, eT and eCeT treatments respectively. The difference in biomass under OF and AC was not significant. The increase in grain yield over ambient varied from 30% under eT to 51% and 65% under eC and eCeT treatments respectively. The seed index as measured through weight of 100 numbers of seeds, was significantly higher under elevated CO_2 and/or elevated temperature treatments than the ambient chamber and open field treatments.

Keywords: Carbon dioxide fertilization, climate change, elevated temperature, seed index, soybean biomass.

INDUSTRIAL revolution along with increased fossil-fuel burning has caused a large increase in the atmospheric concentration of three key greenhouse gases (GHGs). Since 1750, the concentrations of the three GHGs, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased by 40%, 150% and 20% respectively. According to the 5th Assessment Report (AR) of the Intergovernmental Panel on Climate Change (IPCC), among the total anthropogenic CO_2 emissions between 1750 and 2011, about half have occurred in the last 40 years[1]. The atmospheric CO_2 concentration is increasing at an unprecedented rate and for the first time in recorded history has crossed 400 ppmv (parts per million by volume). Considering a value of 280 ppmv in 1800 (prior to the Industrial Revolution), the increase is by about 120 ppmv. According to the measurement at Mauna Loa Observatory in Hawaii, the largest year-to-year increase occurred during the two consecutive years of 2015 and 2016, with the annual growth rate of more than 3 ppmv in both the years[2]. The steep annual growth rate of atmospheric CO_2 particularly in the last few years is significant in the context of global warming and climate change. In addition, there has been an increase of 0.85°C in the global mean surface temperature over the period 1880–2012 according to the 5th AR of the IPCC[1]. The period from 1983 to 2012 was likely the warmest 30-year-period in the last 1400 years in the northern hemisphere. The global mean surface temperature is projected to increase further under all the representative concentration pathways (RCPs). According to the 5th AR of the IPCC, the RCPs describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The increase in global mean surface temperature by 2080–2100 is in the range 0.3–1.7°, 1.1–2.6°, 1.4–3.1°C and 2.6–4.8°C under RCP 2.6, 4.5, 6.0 and 8.5 respectively[1].

The rising CO_2 concentration and increase in global surface temperature have a direct linkage with the growth and metabolism of plants. As CO_2 is a primary raw material in the process of photosynthesis, increase in atmospheric CO_2 concentration has been reported to cause fertilization effect resulting in enhanced crop biomass and yields, particularly in C_3 plants[3,4]. This has been primarily attributed to the enhanced rate of photosynthesis

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upon exposure to higher CO_2 levels[3,4]. However, the CO_2 fertilization effect may be modified under increased surface temperature conditions. Indian studies on the effect of climate change on cereals like rice and wheat have shown improved growth and yield parameters in wheat and rice[5,6]. In another study, adverse impact of climate change on growth attributes of rice in South Indian conditions has been reported[7]. Soybean (*Glycine max*) is an important *kharif* crop in major parts of central India[8]. However, information from field studies regarding climate change impact on soybean crop in Indian conditions is lacking. Hence, the present study was carried out to investigate the effect of elevated CO_2 and elevated temperature on growth and yield attributes of soybean crop under field conditions using open top chambers (OTCs).

Materials and methods

Soil and climate

The study was taken up as a field experiment in OTCs of 4 × 4 m size at the research farm of the Indian Institute of Soil Science, Bhopal. The study site is located at 23°15′N lat and 77°25′E long, at 427 m amsl and is characterized by a humid subtropical climate with mild, dry winters and a hot summer followed by a humid monsoon season. The soil of the experimental site is a deep Vertisol (Isohyperthermic Typic Haplustert) with clay texture (52% clay) and is characterized by slightly alkaline pH (average pH of 7.96), low salt content and low organic matter content.

Experiment facility

To study the effect of possible climate change, five climate treatments were chosen for the experiment. These were: open field (OF), ambient chamber (AC), elevated temperature (eT), elevated CO_2 (eC) and elevation of both temperature and CO_2 (eCeT). Except the open field plots, all the other four treatments were grown in the OTCs. Carbon dioxide was elevated to the level of 550 ppmv and temperature was increased by 2.0°C above the ambient chamber. The OTCs were open from the top and constructed using polycarbonate sheets from four sides having 4 m × 4 m land area. Arrangements were made for supply of CO_2 gas (99.5% purity) to the OTCs through connected nozzles, and elevation in temperature was realized through infrared heaters.

Crop culture

Soybean crop, cultivar JS-20-29, was grown in the *kharif* season of 2016 with recommended dose (30–60–40 kg ha^{-1}) of N, P_2O_5 and K_2O in the OTCs and open field. In addition, vermicompost @ 2 tonnes/ha on dry weight basis was also applied in all the treatments. Soybean was sown in the middle of July as a rainfed crop. All the nutrients and vermicompost were supplied as basal dose at sowing. The crop was sown with a row–row spacing of 40 cm and plant–plant spacing of 15 cm. The plots were maintained weed-free with three hand weedings at 15, 30 and 60 days after sowing (DAS). The crop was protected from insect attack by spraying chloropyriphos 25 EC and trizophos 40 EC @ 1.5 and 0.75 lit/ha respectively.

Biophysical observations

The climate change impact was studied in terms of selected plant growth parameters (viz. plant height, leaf area and aboveground biomass) and yield attributes (viz. number of pods, number of seeds per pod, seeds index and grain yield). Five plants (considered as replications) per treatment were randomly selected for observations on growth parameters and yield attributes. Plant height was measured using a measuring gauge from the surface to the apical bud on five different dates during the active crop growth stage at 34, 41, 48, 55 and 63 DAS. The leaf area and biomass observations were recorded at 50, 60, 70 and 85 DAS. Leaf area of the freshly collected plants was measured using a Leaf Area Meter (LICOR 3100C, USA). Aboveground plant biomass at different crop growth stages was determined by drying the biomass of five selected plants in a hot-air oven at 60°C for 48 h, or till a constant weight. After pod-setting, the number of pods per plant was counted at 70, 85 and 95 DAS and at harvest. The mean values were expressed as the number of pods per plant. The grain yield, aboveground plant biomass and number of seeds per pod were recorded at harvest after exposure to sun-drying in the field. Seed index was determined by taking the weight of 100 numbers of seeds. Crop growth rate (CGR) was estimated for different growth periods from the ratio of increment in biomass value to the number of intervening days.

Statistical analysis

The recorded data on the selected parameters were analysed using analysis of variance (ANOVA) as relevant for completely randomized design (CRD). The data were initially tested to be normally distributed with homogeneity of variances. Effect of the tested factor, viz. climate, was compared at 95% level of significance. For post-hoc analysis, least significant difference (LSD 0.05) test was carried out followed by Duncan's multiple range test (DMRT)[9].

Results and discussion

Plant growth characteristics

Plant height: A significant ($P < 0.05$) effect of CO_2 and temperature was observed on plant height on all the observation dates (Figure 1). Maximum plant height was observed at 63 DAS under all the climate conditions, after which no increase was observed. Compared to open field condition, plants were significantly taller under ambient OTC condition at all the dates of observation, indicating a significant chamber effect. In the initial stage (34 DAS), though plant height was higher under eT condition, it was statistically at par with eC and eCeT conditions. However, plants under the three climate treatments were significantly higher than AC and OF treatments. At 48 DAS, plant height was in the order eT ≈ eCT > eC ≈ AC > OF treatments. However, at 63 DAS, plant height was significantly higher under eT followed by eC and eCeT treatments, the latter two being statistically at par. All the three modified climate treatments were significantly higher than the AC and OF treatments.

Leaf area: Observations indicated significant effect of elevated temperature and elevated CO_2 on plant leaf area (Figure 2) during most of the observation dates. At 50 DAS, the highest leaf area was observed under eT, which was statistically at par with the eCeT treatment. Both these treatments were significantly higher than the eC, AC and OF treatments. At 60 DAS, leaf area was in the order eC ≈ eT ≈ eCeT > AC > OF treatments. However at 70 DAS, there was no significant difference between the treatments. Among the different observation dates, maximum leaf area was observed at 60 DAS for the eC, eCeT and AC treatments, whereas it was 70 DAS for the OF treatment and 85 DAS for the eT treatment. Leaf area at 50 DAS under eC, eT and eCeT treatments was higher by 143%, 281% and 259% respectively, compared to AC treatment. At 60 DAS, the corresponding values of relative gain in leaf area were 50%, 40% and 36% respectively, and the OF treatment showed significantly lower leaf area (lower by 30% than the AC treatment), indicating a significant chamber effect. There was a gradual decrease in green leaf area with pod setting. The absolute values decreased, with leaf area ranging from 1073 cm^2/plant under OF to 1541 cm^2/plant under eCeT treatment at 70 DAS. The treatment difference was not found significant. At 85 DAS, the leaf area in most of the treatments showed a decreasing trend, except the eT treatment.

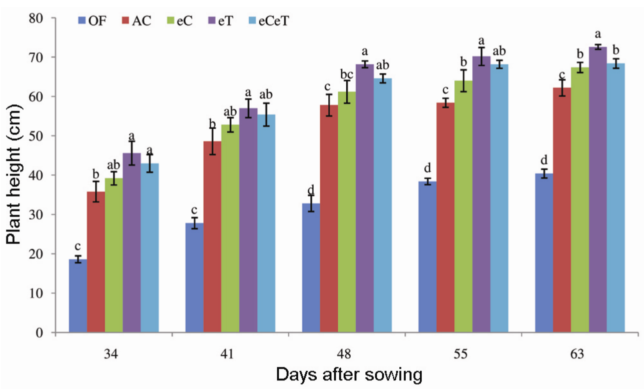

Figure 1. Plant height of soybean during various growth stages under different climate treatments. (OF, Open field; AC, ambient chamber; eC, elevated CO_2; eT, elevated temperature; eCeT, elevated CO_2 and elevated temperature.) Bars with different lower-case letters are significant according to Duncan's multiple range test ($P < 0.05$); Error bars indicate standard error of mean (±SEm).

Aboveground plant biomass and crop growth rate: The observations on aboveground plant biomass, recorded at 50, 60, 70, 85 DAS and at harvest indicated a significant ($P < 0.05$) trend of higher dry matter accumulation under elevated CO_2 and/or elevated temperature conditions at all the sampling dates compared to ambient chamber and open field treatments (Figure 3). There was a steady increase in plant biomass with higher CGR observed during 50 to 70 DAS and 70 to 85 DAS (Figure 4). The CGR values during the growth period of 50–85 DAS were of the order eCeT > eC > eT > AC > OF treatments, but the treatments were not significantly different.

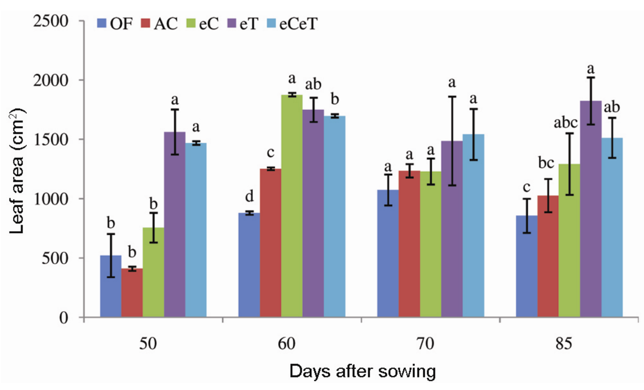

Figure 2. Leaf area of soybean during various growth stages under different climate treatments. Bars with different lower-case letters are significant according to Duncan's multiple range test ($P < 0.05$); Error bars indicate standard error of mean (±SEm).

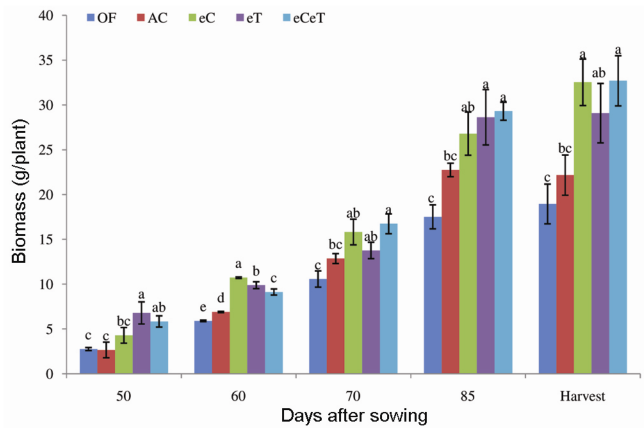

Figure 3. Aboveground biomass in soybean during various growth stages under different climate treatments. Bars with different lower-case letters are significant according to Duncan's multiple range test ($P < 0.05$); Error bars indicate standard error of mean (±SEm).

At 50 DAS, the recorded biomass ranged from 2.67 g/plant under AC to 6.80 g/plant under eT treatment. Compared to AC treatment, the biomass was higher by 61%, 155% and 119% under eC, eT and eCeT treatments respectively. At 60 DAS, the corresponding increase in biomass was 56%, 43% and 32% respectively, compared to AC treatment. At this stage, the biomass values ranged from 5.91 g/plant under OF to 10.74 g/plant under EC treatment. There was rapid increase in the biomass at 70 DAS, with values ranging from 10.58 g/plant under OF to 16.74 g/plant under eCeT treatment. About 7–30% higher biomass was observed under elevated CO_2 and/or elevated temperature treatments compared to ambient chamber treatment. A conspicuous increase in plant growth was observed at 85 DAS under all the climate treatments. The modified climate treatments, viz. eC, eT and eCeT, were statistically at par, but were higher than ambient chamber and open field condition. The treatments were in the order eCeT ≈ eT ≈ eC > AC ≈ OF. Dry matter accumulation after 85 days till harvest was minimal. Compared to AC treatment, 47%, 31% and 47% higher biomass was recorded under eC, eT and eCeT treatments respectively. The difference in biomass under open field and ambient chamber was not significant.

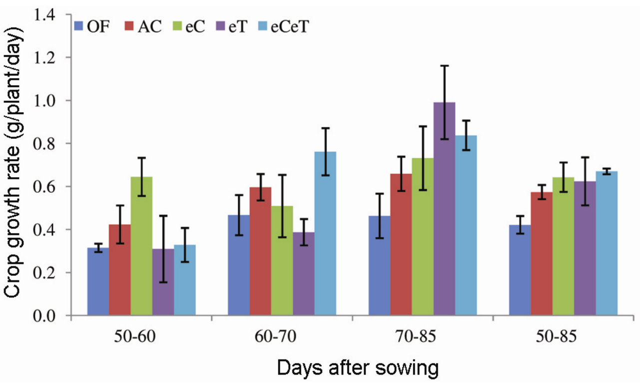

Figure 4. Crop growth rate of soybean under different climate treatments. Error bars indicate standard error of mean (±SEm).

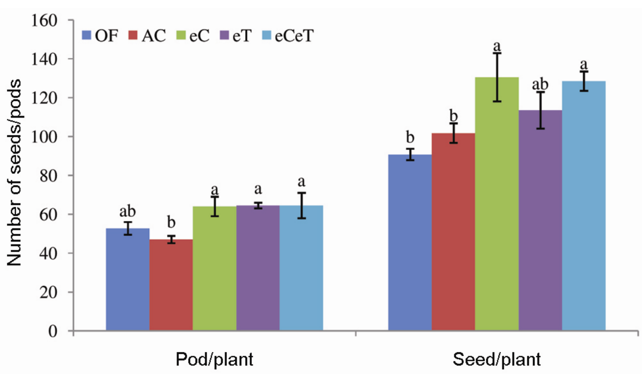

Figure 5. Number of pods and seeds per plant in soybean under different climate treatments. Bars with different lower-case letters are significant according to Duncan's multiple range test ($P < 0.05$). Error bars indicate standard error of mean (±SEm).

Soybean yield and pod attributes

Soybean pod attributes: The number of pods per plant differed significantly ($P < 0.05$) among the treatments, with significantly higher values under modified climate conditions compared to ambient chamber (Figure 5). The OF and AC treatments were statistically at par indicating no significant chamber effect. The number of pods varied from 47 under AC treatment to 64.5 each under eT and eCeT treatments. In the eC, eT and eCeT treatments, 36–37% higher number of pods were observed compared to AC treatment. Effect of change of climate variables was also significant ($P < 0.05$) on the number of seeds per plant. It varied from 90.8 under OF to 130.8 under eC treatment. All the three modified climate treatments showed higher number of seeds per plant compared to ambient chamber and open field conditions. The OF and AC treatments were statistically at par indicating no significant chamber effect. Compared to AC treatment, the increase in the number of seeds per plant was 12%, 26% and 28% under eT, eCeT and eC treatments respectively.

Seed index and grain yield: Effect of elevation in CO_2 and temperature showed a significantly positive effect on seed index (Figure 6) and grain yield (Figure 7). The seed index as measured through weight of 100 number of seeds was significantly higher under elevated CO_2 and/or elevated temperature treatments than the ambient chamber followed by open field conditions. The seed index values varied from 11.28 g under OF to 14.20 g under eC treatment. The three modified climate treatments, viz. eCeT, eC and eT were statistically at par, but were significantly higher than AC treatment, with OF treatment showing significantly lowest seed index. Significant difference between AC and OF treatments indicated a significant chamber effect on individual seed weight.

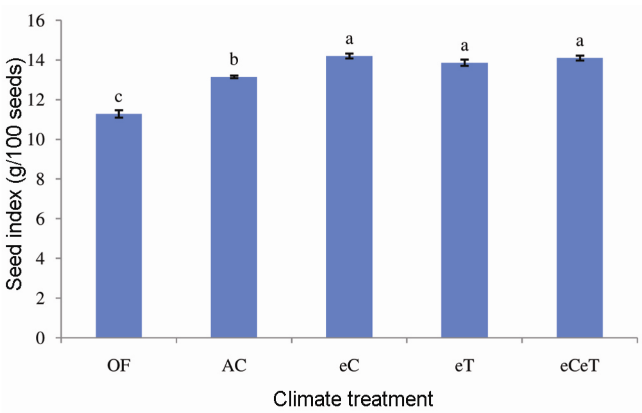

Figure 6. Seed index (100 seed weight) of soybean under different climate treatments. Bars with different lower case letters are significant according to Duncan's multiple range test ($P < 0.05$). Error bars indicate standard error of mean (±SEm).

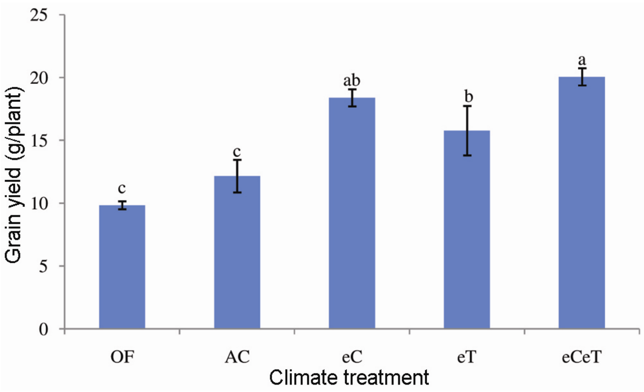

Figure 7. Soybean grain yield under different climate treatments. Bars with different lower-case letters are significant according to Duncan's multiple range test ($P < 0.05$). Error bars indicate standard error of mean (±SEm).

Similar to seed index, significantly higher grain yield was also observed under the three modified climate treatments compared to ambient and field conditions. The observed grain yield in the studied treatments was in the order eCT ≈ eC > eT > AC ≈ OF treatments. The increase in grain yield over ambient varied from 30% under eT treatment to 51% and 65% under eC and eCeT treatments respectively.

Climate change effect on growth attributes of soybean

The observed data indicated a significantly positive effect of CO_2 and temperature, individually as well as in combination, on the studied growth characteristics, viz. plant height, leaf area and aboveground biomass. Elevated CO_2, either alone or in combination with elevated temperature, resulted in increase in biomass at harvest to the extent of 47%, whereas elevation of temperature alone resulted in 31% increase. With elevated CO_2 concentration, about 40% increase in total biomass production was reported in soybean[10] under OTCs, whereas free-air CO_2 enrichment (FACE) experiment at 550 ppmv CO_2 concentration showed 18% increase[11] in soybean biomass. Under elevated CO_2 concentration, the net photosynthesis rate increased due to higher rate of carboxylation and reduced photorespiration[12]. Increase in temperature and CO_2 concentration enhances the rate of biochemical processes and promotes cell proliferation due to higher cell division or cell elongation[7,13,14], thus resulting in increase in plant height and leaf area under elevated CO_2 and elevated temperature conditions. In rice crop under South Indian conditions, positive effect of higher CO_2 and higher temperature on plant height was observed, but the leaf area, dry matter and grain yield were lower under modified climate conditions[7]. The results are in contrast to our findings. This might be due to the higher level of temperature treatment (4°C above ambient) and a higher level CO_2 concentration (650 ppmv) in that experiment[7] compared to ours with 550 ppmv CO_2 and 2.0°C temperature above ambient. However, similar to our results, about 57% higher dry biomass (including root biomass) was reported in soybean grown at 800 ppmv CO_2 concentration under controlled chamber conditions[15]. In another OTC study with lowland rice in eastern India, Bhattacharyya and Roy[6] showed increase in the aboveground biomass to the extent of 19% and 20% under elevated CO_2 and elevated temperature respectively.

Climate change effect on yield attributes of soybean

Soybean grain yield was observed to be significantly higher under elevated CO_2 and/or elevated temperature treatments. The increment in grain yield over the ambient was however higher in treatments with CO_2 elevation than temperature elevation. About 24% increase in grain yield was reported in rice under elevated CO_2 in OTCs[6]. In another experiment, total grain yield in rice increased with elevated CO_2 by 69.6% in ambient temperature, but decreased with elevated temperature by 33.8% in ambient CO_2 due to warming-induced floral sterility[16]. In phytotron growth chambers from a pot experiment, 11% increase in wheat grain yield was observed at 650 ppmv CO_2 compared to a non-significant decrease under elevation of both CO_2 and temperature, and a significant decrease (38%) in grain yield under elevated temperature[5]. The response of plants to elevated CO_2 and temperature grown in pots may be different compared to those grown in fields under OTCs or FACE systems. Photosynthetic acclimation due to nutrient and water limitations in pot experiments may be possible though light-saturated rates of photosynthesis are significantly higher in several C_3 plants under elevated CO_2 grown in field conditions under OTCs or FACE systems[17]. The significantly higher number of pods and seeds per plant as observed in our experiment might be responsible for higher grain yield under elevated CO_2 and/or temperature conditions. The increase in sink capacity is also because of a significantly higher seed index under elevated CO_2 and/or temperature compared to ambient. Alteration in seed number and seed weight per plant in soybean upon exposure to high CO_2 and temperature has also been reported from experiments under controlled environment chambers[18,19]. However, Heinmann *et al.*[18] did not report any change in seed mass due to elevated CO_2, though they observed a significant reduction in seed mass due to increased temperature. On the other hand, our observations are in agreement with several other reports. Similar to our findings, Pereira-Flores *et al.*[19] reported 11% increase in 1000 grain weight in soybean under elevated temperature (2.7°C above ambient) and by 13.5% under the combined effect of elevated CO_2 (750 ppmv) and elevated temperature. A meta-analysis reported positive effect of elevated CO_2 on seed mass in legumes, primarily because of an increase in seed nitrogen per plant[19]. Under elevated CO_2 conditions, higher acquisition of nitrogen by N-fixing legumes enhanced nitrogen acquisition compared to the non-N-fixing plants, leading to higher seed mass[20].

Conclusion

The study showed a significant positive effect of elevated CO_2 and/or elevated temperature on aboveground biomass, leaf area, pod attributes, seed weight and grain yield of soybean. Higher temperature and higher CO_2 resulted in an increase in aboveground biomass and grain yield by 31–47% and 30–65% respectively. However, the effect of temperature increase alone under ambient CO_2 was lower than the effect of CO_2 increase alone under ambient temperature and increase of both CO_2 and temperature. The seed index as measured through weight of 100 number of seeds, was significantly higher under elevated CO_2 and/or elevated temperature treatments than the ambient chamber and open field treatments. The positive effect of elevated CO_2 was not observed to be retarded with increase in temperature. However, further studies are needed to investigate the effect of elevated CO_2 under higher temperature conditions.

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