Effect of elevated atmospheric CO_2 concentrations on growth and yield of blackgram (*Vigna mungo* L. Hepper) – a rainfed pulse crop

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ABSTRACT

The response of blackgram (*Vigna mungo* L. Hepper) to two levels of elevated carbon dioxide (550 and 700 ppm) in terms of growth and yield was investigated and compared with ambient CO_2 level (365 ppm) using open-top chambers. The growth parameters *viz.*, length and weight of root and shoot, root:shoot ratio, leaf area and weight significantly increased at 700 ppm CO_2 when compared with 550 ppm. The percentage increase in total biomass at 700 and 550 ppm CO_2 was 65.4% and 39%, respectively compared to the ambient (chamber) control. The increase in total seed yield at 700 ppm (129%) was due to an increase in number of pods per plant and 100 seed weight, whereas at 550 ppm (88.7%) it was due to an increased number of pods/plant and seeds/pod. The results indicate variable responsive effects at different levels of CO_2 emphasizing the pertinence of research on elevated CO_2 in various agroecological inhabitations all over the world. The indication of higher responses for root and leaf at initial growth stages at the higher elevated level of CO_2 (700 ppm), which leads to better root establishment, achieving early photosynthetic efficiency and also better biomass production, and its improved partitioning can be reckoned as a positive aspect of increasing concentrations of CO_2 in atmosphere. The harvest index increased significantly to 35.7 and 38.4% at 550 and 700 ppm, respectively; it is a very important phenomenon in pulses for breaking the yield barrier.

Keywords: elevated carbon dioxide; blackgram; growth; yield; open-top chambers

The increasing concentration of CO_2 in atmosphere is caused by anthropogenic emission and human activities (Houghton et al. 2001). The increase in CO_2 was about 64 ppm (Krull et al. 2005) during the last fifty years (1953 to 2003) and it has affected the plant growth and photosynthesis. Most of the relevant studies focused on the effects of CO_2 enrichment on biomass accumulation in plants (Drake et al. 1997). Kimball (1983, 1986), Kimball et al. (2002) and Poorter (1993) on the basis of their evaluation of several hundreds of studies of this kind showed an average increment in biomass production in C_3 plants more in response to a doubling of CO_2 concentrations. Cure (1985) and Cure and Acock (1986) conducted a literature survey and tabulated the results of a doubling of CO_2 on the response of 10 major agricultural crops under 550 µmol/mol CO_2 and they reported yield increase of wheat, rice, cotton and potato by 19, 8, 113 and 28%, respectively. Because of the economic importance, over the past century there were numerous observations on the effects of elevated CO_2 and yield of agricultural crops (Kimball 1986). However, with impending global change and the need to secure food supplies for the future, several CO_2 enrichment experiments have concentrated on agricultural crops, with yield serving as an important economic parameter.

The pulse crops showed a better response to elevated CO_2 levels. Earlier studies with cowpea grown in controlled environmental chambers showed positive growth responses to elevated CO_2 (Mbikayi et al. 1983). Greengram grown under CO_2 enrichment was taller and attained a greater leaf area along with dry matter than ambient CO_2 grown plants at initial growth stages (Srivastava et al. 2001). Under elevated CO_2 (600 ppm) and well-watered conditions the response of blackgram at initial growth stages was higher than sorghum

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and sunflower (Vanaja et al. 2006b). Blackgram [*Vigna mungo* (L.) Hepper] is an important source of protein and is cultivated as short duration rainfed crop in semiarid areas of South Asian countries. An attempt was made in this paper to quantify the response of blackgram to two enhanced CO_2 levels (550 and 700 ppm) in terms of growth and yield.

MATERIAL AND METHODS

Experimental conditions and plant material

The seeds of blackgram cv. T-9 were sown in six open-top chambers (OTCs) lined with transparent PVC sheet each having 3 m × 3 m with 3 m height. The seeds were sown directly in the soil (Alfisol) to study the plant growth and yield responses to two elevated CO_2 levels, i.e. 550 ppm and 700 ppm and ambient (365 ppm) level. Each chamber had four 1 m × 1 m plots with five rows and minimally ten plants in each row were maintained. The experimental site was sandy loam in texture, neutral in pH (6.8), low in available nitrogen (225 kg/ha), phosphorus (10 kg/ha) and medium to high in available potassium (300 kg K_2O/ha).

To maintain the elevated levels of CO_2 concentration in OTCs to 550 ppm and 700 ppm at crop canopy level, continuous injecting of 100% CO_2 into plenum of OTCs was done where it was mixed with air from air compressor before entering into the chamber. The air sample from each chamber was drawn from the center point of OTC at three-minute interval into a non – dispersive infrared (NDIR) CO_2 analyzer (California Analytical) and the set level of CO_2 concentration was maintained with the help of solenoid valves, rotameters, Program Logic Control (PLC) and Supervisory Control and Data Acquisition (SCADA) software. Throughout the experimental period continuous measurements of relative humidity and temperature were possible with the sensors fitted inside the chambers (Vanaja et al. 2006a). The temperature of the chambers with elevated CO_2 remained the same as in the ambient air chambers but 1–2°C higher than in the outside field. The light intensity in the chambers was 80–85% of the outside field; however gentle washing of polythene cover was frequently required to maintain transparency. Plants were maintained stress-free by irrigation and by application of recommended doses of fertilizers.

For each treatment two OTCs were maintained, i.e. two OTCs at 550 ppm and two OTCs at 700 ppm. The elevated levels of CO_2 were maintained 24 h a day from the sowing to final sampling. Two OTCs were at ambient CO_2 level (365 ppm) without any external CO_2 supply and served as chamber control (Ch-control).

Plant growth measurements

The plant growth observations were recorded at 7, 14, 21, 28, 45 and 60 days after sowing (DAS), two replications from each chamber consisting of three plants for each replication, i.e. four replications with twelve plants for each treatment were harvested by uprooting the plants carefully. The roots were made free from soil particles by gentle washing with water and the plants were separated into roots, stems and leaves. The length of root and shoot was recorded and root volume of plant roots (as ml of water displaced) was expressed as ml/10 plants. The total leaf area at different time intervals was measured with photo-electronic leaf area meter (LI-3100, LI-COR) and expressed as cm^2/10 plants. Dry weights of stem, root and leaf were recorded after drying the plant parts at 80°C for 48 hours in an oven till constant weights were attained. Specific leaf weight and root:shoot ratio were calculated with the recorded values. The percentage increment of each parameter at different growth stages was calculated for 700 ppm and 550 ppm over chamber control and also for the differences in response to an increase of CO_2 level from 550 to 700 ppm.

Final harvest and yield

Yield measurements were made after final harvest at 90 DAS and ten plants per replication were harvested to record the yield and yield components of each treatment. Number of pods, pod weight and seed weight were recorded and expressed as g/10 plants. The data were statistically analyzed using a two-way analysis of variance (ANOVA) to test the significance of treatments, conditions and their interactions.

RESULTS

Plant growth analysis

Blackgram showed a positive growth response to elevated CO_2 levels in terms of root length, shoot length, leaf area and total biomass production. It was also observed that the response to enhanced CO_2 level was higher at 700 ppm than at 550 ppm for all the characters studied.

The ANOVA for shoot length, root length and root shoot ratio was significant for time intervals and conditions, whereas for leaf area, leaf dry weight, shoot dry weight, root dry weight and total dry weight the conditions, time intervals and their interaction were found highly significant (Table 1).

Shoot length recorded significant increase with enhanced CO_2 levels and the values at 700 ppm were higher than at 550 ppm. The increment in shoot length varied from 9 to 34% with 700 ppm, 2 to 21% with 550 ppm at different growth stages when compared with the chamber control and the maximum response was recorded at 45 DAS for both elevated CO_2 concentrations (Figure 1). The increased response of shoot length due to CO_2 level enhanced from 550 ppm to 700 ppm showed a different trend, and the response was highest at 21 DAS (19.9%). The stem dry weight increased about 4 to 23% under 550 ppm and about 7 to 80% with 700 ppm of CO_2 level at different growth stages above the chamber control values (Figure 2) and the maximum response was at 28 DAS at 700 ppm, 550 ppm and also in case of the increment in CO_2 level from 550 ppm to 700 ppm (46%).

The response of root length, root dry weight and root volume was positive and significant at 550 ppm and 700 ppm levels of CO_2, as well. The percentage increment of root length varied from 2 to 18% with 550 ppm between 7 and 60 DAS, whereas it was 22.5 to 38% under 700 ppm with a maximum response at 45 DAS (Figure 1). The improved response due to CO_2 concentration increased from 550 to 700 ppm was more significant at initial growth stages (7 DAS). The root volume was measured at 30 and 60 DAS and the increase in root volume under 700 ppm was 39.5 and 23%, respectively; however, with 550 ppm the higher response was observed only at 60 DAS (10.8%) and with the increase in CO_2 from 550 to 700 ppm the root volume increased by 37.5 and 13% during these days of observation. The root dry weight at 700 ppm was 9 to 61% higher than the chamber control at different growth stages, whereas the increment at 550 ppm was 3 to 30% (Figure 2). The maximum response was at 28 DAS for root dry weight in all the treatments.

The biggest leaf area was recorded at 45 DAS in all the treatments and the response was strongest at 700 ppm followed by 550 ppm. The percentage increase in leaf area ranged from 18 to 90% during 7 to 60 DAS at 700 ppm, whereas it was 5.4 to 28.6% at 550 ppm. The response of leaf area to the increase in CO_2 from 550 to 700 ppm was high at early stage of germination (59.4%) and also at 45 DAS (58.7%). The leaf dry weight response followed the trend of leaf area and at 45 DAS it reached the maximum in all the treatments. The response of leaf dry weight to different levels of enhanced CO_2 over chamber control showed a different trend. At initial growth stages (up to 14 DAS) the response was very high to both enhanced CO_2 levels hence the difference between 700 and 550 ppm CO_2 level was not so significant. The trend was reversed after 28 DAS; a decreasing tendency showed at 550 ppm compared to Ch-control, whereas an upward trend was observed at 700 ppm.

Table 1. ANOVA for various growth characters of blackgram and their response to elevated CO_2 levels (550 and 700 ppm) and chamber control (365 ppm) at 60 DAS

Source	*df*	Mean sum of squares							
		total dry weight	root dry weight	stem dry weight	leaf dry weight	root:shoot ratio	leaf area	shoot length	root length
Replication	3	0.22	0.71**	0.45	13.98	0.00	766 635	5.17	14.24
Conditions	2	790.94**	2.02**	92.15**	330.37**	0.004**	52 212 990**	145.48**	29.82**
Time intervals	5	11 350.58**	43.53**	2 089.63**	3 704.23**	0.010**	577 188 900**	3 815.46**	421.58**
Condition × time intervals	10	217.19**	0.56**	36.24**	92.98**	0.001	24 076 900**	26.83	7.25
Error	51	4.78	0.08	0.88	8.96	0.001	378 730	18.42	5.31

*statistically significant at $P < 0.05$, **statistically significant at $P < 0.01$

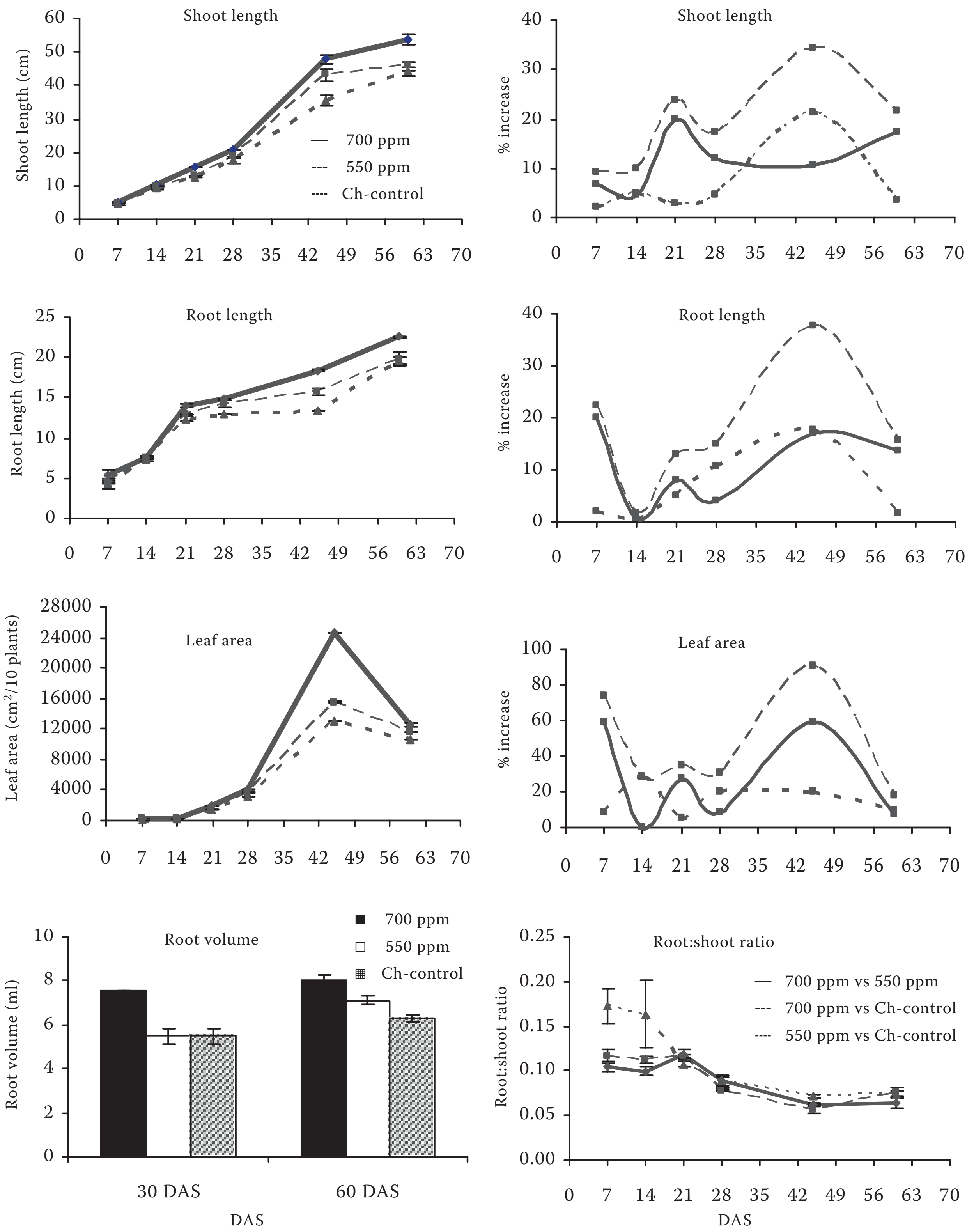

Figure 1. The stem and root length, leaf area, root volume and root:shoot ratio of blackgram at different growth stages under elevated CO_2 (700 ppm and 550 ppm) and ambient (365 ppm) conditions

The root:shoot ratio showed a different tendency. Under Ch-control condition the ratios were significantly higher at initial growth stages (up to 14 DAS), however the difference between treatments narrowed at later stages.

The total biomass showed a significant and positive response at all the growth stages under enhanced levels of CO_2, with much higher response under 700 ppm (Figure 2). The percentage increment in total biomass ranged from 2 to 31% at

550 ppm and from 28 to 70% at 700 ppm, and the highest response was recorded at 28 DAS for both levels of CO_2, whereas the response continued to be high up to 45 DAS in the case of the increase of the CO_2 level from 550 to 700 ppm.

Yield and harvest index

All the yield parameters recorded a significant increment at 550 and 700 ppm CO_2 over chamber control and also in the case of the increment in CO_2 concentration from 550 to 700 ppm. The yield parameters viz., number of pods (18.4, 51.3, 27.8%), pod weight (86.8, 119.7, 17.6%), seed weight (88.7, 128.9, 21.3%) and 100 seed weight (2.3, 51, 47.6%) were increased under elevated CO_2 levels (550 ppm and 700 ppm) compared to the chamber control, as well as to the concentration increase of CO_2 from 550 to 700 ppm (Table 2). The number of seeds/pods (56, 0.23, –55.6) showed a different response, as higher values were recorded at 550 ppm than at 700 ppm.

The total biomass and harvest index also increased under elevated CO_2 levels. The percentage increase of biomass was 65% at 700 ppm and 39% at 550 ppm, whereas the harvest index recorded an increase of 38.7 and 39.5% at 550 ppm and 700 ppm, respectively, compared with the chamber control. However, the harvest index improved by 2% with 150 ppm increment in CO_2 level above 550 ppm.

DISCUSSION

The growth and yield response of blackgram to two elevated CO_2 levels (550 and 700 ppm) was found positively significant. The increased root length, root mass and root volume under elevated CO_2 levels implies the probability of deeper soil penetration and spread to more volume of soil, which would be an advantage in a drier climate. CO_2 enrichment in general strongly enhanced the root growth by increasing its length, volume and weight. Root volume was also increased under elevated CO_2 conditions due to more lateral roots and root hair formation. The response level of these parameters at different growth stages varied as the crop growth progressed. At 700 ppm the high response was observed during germination stage (7 DAS) and also at 45 DAS; this was not the same at 550 ppm. This clearly indicates that the increment in CO_2 levels from 550 to 700 ppm will be different and a shift in the response may be expected.

The shoot length also increased with enhanced levels of CO_2. The response with 550 and 700 ppm CO_2 showed a different pattern at different growth stages. A high response was recorded in blackgram at 21 and 45 DAS with 700 ppm with a higher magnitude, whereas with 550 ppm it was only at 45 DAS. The stem dry weight showed increased values at both levels of enhanced CO_2 with a similar response pattern showing a high response at 28 DAS. The magnitude was very high with 700 ppm and there was more than 40% increase in response to increasing CO_2 level from 550 to 700 ppm.

The response of leaf area and leaf weight to two levels of CO_2 showed a different pattern even though both enhanced CO_2 levels recorded higher values when compared with ambient level of Ch-control conditions. In case of the increment of CO_2 by 150 ppm from 550 to 700 ppm, a clear shift in response pattern was observed. As it was noticed with root length, there was a significantly higher response of leaf area to 700 ppm at germination level and also at 45 DAS, which was missing at 550 ppm. The response of leaf weight to both levels followed the same trend up to 28 DAS and thereafter it showed a reverse tendency. The increment in leaf area and leaf dry weight at higher levels of CO_2 could result from the level of CO_2 at later growth stage increased over 550 ppm, which significantly enlarged not only leaf area but also leaf weight.

The response of total biomass at both levels followed the same trend showing the maximum response at 28 DAS, which is coinciding with flower initiation. The magnitude of the response was maintained high till the end of the growth period with 30 to 40% higher response to CO_2 level increased from 550 to 700 ppm. The increase in both stem and leaf growth with elevated CO_2 caused an overall increase in total biomass in blackgram at initial stages of growth under irrigated conditions (Vanaja et al. 2006b). Similar reports with *Vigna radiata* L. also showed an increase in total biomass under elevated CO_2 conditions (Srivastava et al. 2001). The root:shoot ratios were higher under ambient conditions compared with elevated CO_2 levels in blackgram and resulted from a stronger response of shoot weight than root weight response.

The increased CO_2 level in atmosphere not only improved the shoot and root biomass but also yield and its components. Pod, seed yield and seed weight

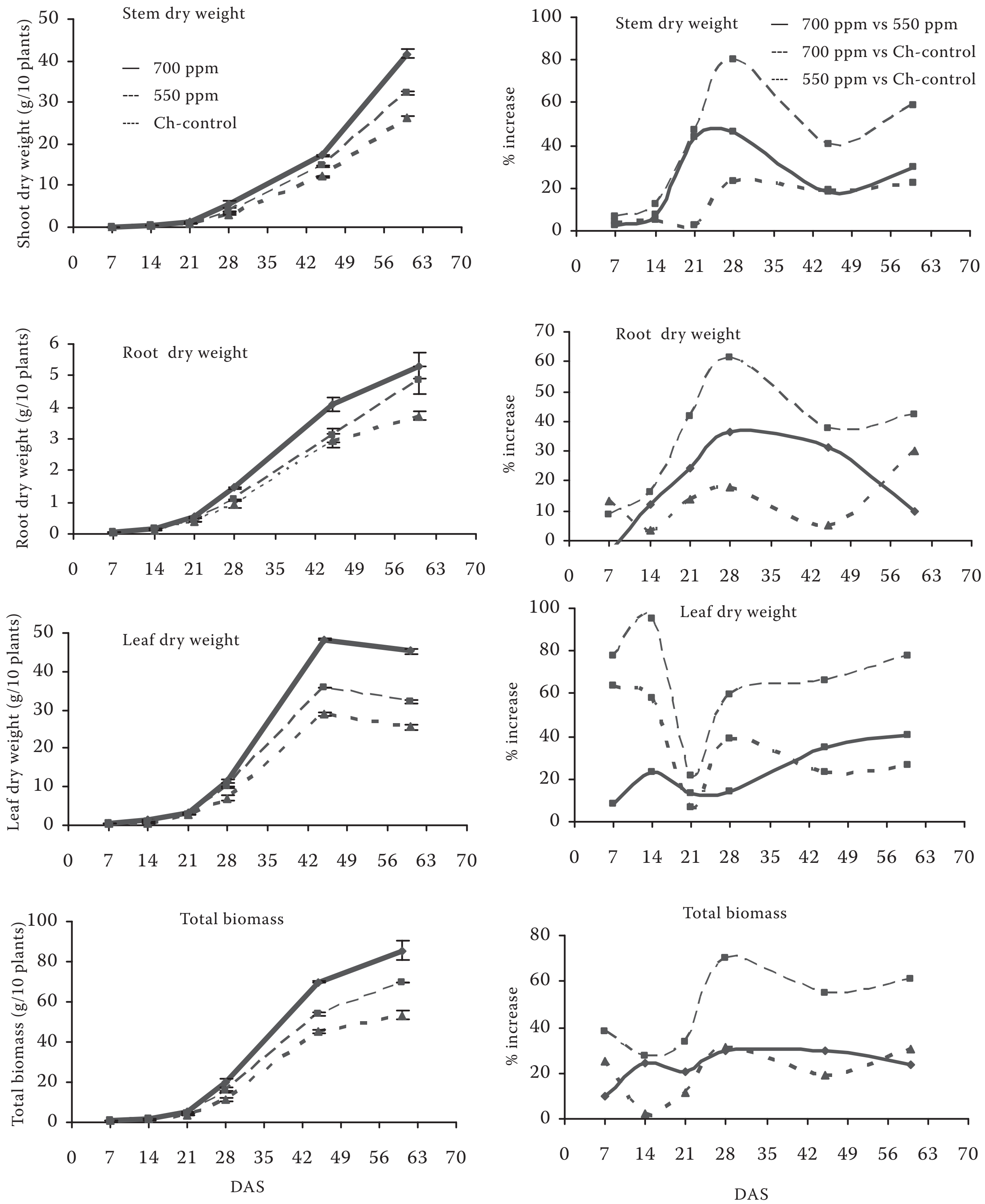

Figure 2. The stem, root, leaf dry weight and total biomass of blackgram at different growth stages under elevated CO_2 (700 ppm and 550 ppm) and ambient (365 ppm) conditions

of soybean increased with CO_2 enrichment as reported by Heinemann et al. (2006). In the present study, the improvement in pod number, pod weight and seed size was observed under CO_2 enrichment. It is interesting that the increased pod number and number of seeds per pod at 550 ppm were caused by increased seed yield, whereas it was due to pod number and seed size at 700 ppm. Rogers and Dahlman (1993) have compiled a synopsis of dry matter production and yield increase of the

Table 2. Yield parameters of blackgram (for 10 plants) under elevated CO_2 levels of 550 and 700 ppm over the chamber control (365 ppm)

	Treatments			Increase (%)		
	Ch-control	550 ppm	700 ppm	550 ppm vs. Ch-control	700 ppm vs. Ch-control	700 ppm vs. 550 ppm
Total biomass	61.1	84.9	101.1	39.0	65.4	19.08
No. of pods	158	187	239	18.4	51.3	27.81
Pod weight (g)	35.6	66.5	78.2	86.8	119.7	17.59
Seed weight (g)	17.4	32.9	39.9	88.7	128.9	21.28
100 seed weight (g)	2.59	2.65	3.91	2.3	51.0	47.55
Seeds/pod	4.25	6.63	4.26	56.0	0.23	–55.6
Harvest index	28.5	38.7	39.5	35.7	38.4	2.07

ten most important crop species in response to elevated CO_2. Their work shows that in some species there was a relative increase in total biomass and in other studies it was economic yield which was greater. Prasad et al. (2002) reported that elevated CO_2 increased seed yield up to 24% in kidney bean (*Phaseolus vulgaris*). The results obtained from the present study showed an increase in the dry matter production as well as economic yield both at 550 and 700 ppm. The seed yield improved by 21% with 150 ppm increase in CO_2 from 550 to 700 ppm, whereas the harvest index (HI) increased only by 2%. This clearly shows that the CO_2 levels increased above 550 ppm improve both biomass and economic yield. Thus it may be concluded that blackgram is positively responding to increasing CO_2 not only for biomass but also for economic yield.

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