Response of Soybean Growth to Elevated CO_2 Conditions

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ABSTRACT: The study examined the effects of CO_2 enrichment on growth of soybean (*Glycine max*). Two soybean varieties were used, Taekwang and Cheongja. The plants were grown in growth chambers with a 12-h photoperiod and a day/night temperature of 28/21°C at the seedling stage and 30/23°C from the flowering stage. The plants were exposed to the two elevated CO_2 levels of 500 and 700 ppm and the ambient level of 350 ppm. Results of the experiment showed that at the second-node trifoliate stage of the two varieties, the elevated CO_2 increased plant height, leaf area and dry weight. The elevated CO_2 also raised the photosynthetic rate of soybean as compared to the ambient level. From the beginning bloom stage to the full maturity stage of the two varieties, the elevated CO_2 increased plant height, leaf area, seed weight and photosynthetic rate. The stomatal conductance and transpiration rate decreased on long days relative to short days of treatment. Through the entire stages, the elevated CO_2 increased the water use efficiency of soybean plants because stomatal conductance and transpiration rate decreased at the elevated CO_2 levels relative to the ambient level.

Keywords : CO_2 enrichment, soybean, photosynthetic rate, stomatal conductance, transpiration rate, elevated CO_2

The acceleration of industrial development has continuously increased the emission of carbon dioxide into the atmosphere. The atmospheric CO_2 level increased from 315.98 to 377.38 ppmv from 1959 to 2004, showing 1.4 ppmv annual increment (Keeling & Whorf, 2005). Consequently the influence of elevated CO_2 to soybean growth has been extensively investigated and many research results have been produced (Ackerson *et al.*, 1984; Allen *et al.*, 1991; Ferris *et al.*, 1999). The research on plant responses to the greenhouse gas concentration by the use of environment-controlled growth chambers showed an association and responses to a rise in the temperature (Pickering *et al.*, 1994), as well as an important variation in the physiological development and the grain yield (Baker & Allen, 1993; Allen & Boote, 2000).

As the CO_2 level was on the rise in soybean growing, so were the photosynthetic rate, leaf area and grain yield (Jones *et al.*, 1984, 1985a, b, c; Valle *et al.*, 1985; Çampbell *et al.*, 1990; Allen *et al.*, 1990). Soybean yield showed less response to the elevated CO_2 than photosynthetic and plant weight reponses (Grashoff *et al.*, 1995; Wand *et al.*, 1999). To maintain and increase soybean yield, it is important to find the varieties that can maximize the potential photosynthetic advantages under the elevated CO_2 level (Ziska *et al.*, 1997). Prior & Rogers (1995) reported that some soybean varieties showed little difference in plant dry weight at the vegetative growth period and only 7% increase of grain yield when CO_2 enrichment was about twice the ambient atmospheric level. Allen *et al.* (1991), however, reported that the same varieties showed 45% increase in plant dry weight at the vegetative growth period and 20% difference in grain yield. Similarly, Ferris *et al.* (1999) reported that certain soybean varieties showed 1% difference in grain weight while Ziska *et al.* (1997) reported 42% grain weight increase in the same varieties. The water use efficiency of soybeans increased under the elevated CO_2, and transpiration rate increased at the rate of 4~5%/°C in the range of 28~35°C (Jones *et al.*, 1985a, 1985b, 1985d).

Curry *et al.* (1995) utilized the climate change model and predicted that soybean yield would decrease if the temperature rose 5°C in the Southwest of America (Allen & Boote, 2000).

To maximize the soybean yield under increasing CO_2 levels, it will be necessary to select the most suitable varieties that can overcome regional weather conditions like the elevated atmospheric CO_2 and temperatures.

This experiment will serve as a basic study to develop crops that can adjust to the elevated atmospheric CO_2 level due to global warming. Parameters analyzed include developmental characteristics, yields, photosynthetic rate, evaporation rate and photosynthesis-related characteristics under elevated CO_2.

MATERIALS AND METHODS

This experiment was conducted in 2005 using the CO_2-controlled plant growth chamber in an artificial weather room of National Institute of Crop Science (NICS). Experiment was performed on two varieties, Taekwang and

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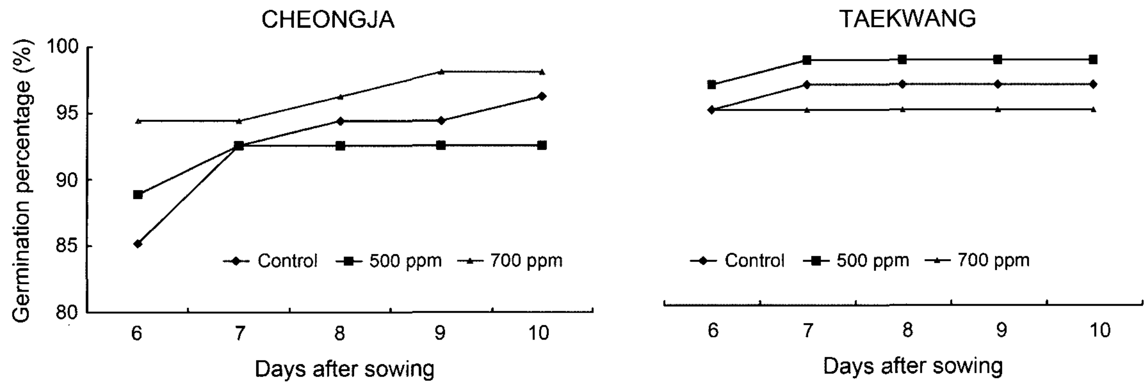

Fig. 1. Emergence responses of soybean to CO_2 enrichment.

Cheongja, treated with CO_2 at the following levels: 350 (ambient level), 500, and 700 ppm. The treatment lasted for 14-40 days at the germination, V2 and R1 stages, respectively. During the flowering stage, the CO_2 treatment lasted from right before the blooming until the full maturity stage. CO_2-controlled chambers were utilized for soybean growing and the purity of CO_2 was maintained at 99.99%.

The luminosity within the chamber was 900 μmol m^{-2} s^{-1}. Temperatures were maintained at 24°C (max 28°C/min 21°C) at the germination and V2 stage, and 26°C (max 30°C/min 23°C) at the flowering stage. The humidity was maintained at 70~80%, and photoperiod 12 hours. The two varieties were sowed at the wagner pot (1/5000a) and treated into the growing chamber during the germination stage, and then grown in the greenhouse. Fertilization and care were given according to the usual pot growing method. Investigations were done three times after each growing stage treatment for 7~25 days at the interval of 7~10 days. The effects of the treatments on the following parameters were analyzed: developmental characteristics, photosynthetic rate, chlorophyll content, and yield-related characteristics. About photosynthesis-related characteristics, the amounts of photosynthesis, transpiration rate and stomatal conductance were investigated by the use of the Li-6400 (USA). Chlorophyll content was investigated by the use of SPAD-502 (Japan).

RESULTS AND DISCUSSION

Germination Stage

The emergence responses of Cheongja (Fig. 1) at the 500 and 700 ppm CO_2 levels were higher than the control from sowing until 6 days after, but those of Taekwang showed little differences. Seven days after sowing, both Taekwang and Cheongja showed more then 93% germination rate regardless of CO_2 level. Results indicate that CO_2 level does not affect the germination rate of soybeans.

V2 Stage

Table 1 shows the results of analysis on soybean growth and photosynthetic rate at V2 stage. Increasing the CO_2 concentration resulted to a corresponding increase in the stem length of Cheongja at around the 7th and 10th day after the treatment. At around the 14th day, the stem length decreased more in the 500 ppm treatment than in the other treatments. Leaf area and dry weight increased in the enriched CO_2 treatments 7-14 days after the treatment. Dry weight of roots stayed roughly the same regardless of CO_2 level. Photosynthetic rate increased as the CO_2 level rose, but showed little difference among the 7th, 10th and 14th day after the treatment.

For Taekwang, enriching CO_2 resulted to an increase in plant height, leaf area and top dry weight on the 7th, 10th, and 14th day after treatment. Very little difference was observed for root dry weight until the 10th day after the treatment, but around the 14th day higher root dry weight was observed in the 500 ppm and 700 ppm treatments than the control treatment. In the case of Taekwang, photosynthetic rate increased as the CO_2 level increased, but showed little differences between the 7th, 10th, and 14th day after treatment.

Flowering Stage

Table 2 shows the growth and photosynthetic rate according to the CO_2 concentration at the flowering stage. Varying the CO_2 level did not affect the plant height of Cheongja at the 7th, 10th, and 14th day. However, longer treatment period and higher CO_2 concentration resulted to larger leaf area. On the other hand, top dry weight showed a big difference. From the 7th day after the treatment, pods started to develop and pod weight increased as the CO_2 treatment concentration increased.

Unlike in V2 stage, root dry weight increased in the flow-

Table 1. Effects of CO_2 enrichment on the growth and photosynthetic rate of two soybean varieties under V2 stage.

Cultivar	Period (days)	CO_2 (ppm)	Plant height (cm)	Leaf area (cm^2/pl.)	Top dry weight (g/pl.)	Root dry weight (g/pl.)	Photosynthetic rate [a]
Cheongja	7	Control [b]	26.9	232	0.7	0.1	11.3
		500	27.8	250	0.9	0.2	14.4
		700	29.3	256	2.4	0.1	21.0
	10	Control	35.9	293	0.8	0.3	8.8
		500	36.0	311	1.0	0.3	12.3
		700	44.3	331	2.4	0.4	17.8
	14	Control	53.8	389	1.5	0.5	14.6
		500	50.5	395	1.7	0.5	15.9
		700	58.1	410	3.1	0.5	20.8
Taekwang	7	Control	33.0	201	0.6	0.1	14.4
		500	33.2	205	1.2	0.1	20.7
		700	33.8	207	1.9	0.3	21.8
	10	Control	37.6	210	0.8	0.3	11.8
		500	38.4	213	1.4	0.3	15.6
		700	42.6	230	2.0	0.3	20.0
	14	Control	63.4	294	0.9	0.5	12.6
		500	63.7	304	1.7	0.7	17.0
		700	68.0	345	2.9	0.7	19.8

[a] Photosynthetic rate : $\mu mol\ m^{-2}\ s^{-1}$, [b] Control : 350 ppm

Table 2. Influence of CO_2 enrichment on the growth and photosynthetic rate of two soybean varieties at the start of bloom stage.

Cultivar	Period (days)	CO_2 (ppm)	Plant height (cm)	Leaf area (cm^2/pl.)	Top dry weight (g/pl.)	Pod dry weight (g/pl.)	Root dry weight (g/pl.)	Photosynthetic rate [a]
Cheongja	7	Control [b]	70.6	1,471	8.2	0	2.5	6.1
		500	66.5	1,507	11.1	0	2.8	12.8
		700	71.9	1,518	11.9	0	2.9	15.5
	14	Control	77.9	1,857	12.2	0.3	1.6	11.9
		500	75.3	2,337	17.6	1.2	2.4	22.5
		700	72.3	2,352	17.7	1.3	2.5	29.4
	21	Control	76.7	1,944	11.4	4.1	2.3	13.8
		500	89.0	2,513	18.9	5.6	4.2	16
		700	80.0	3,403	20.6	6.1	3.8	18.6
Taekwang	7	Control	53.6	1,602	7.9	0	2.9	6.7
		500	59.9	1,762	10.4	0	3.0	20.8
		700	56.9	1,916	11.6	0	3.1	21.6
	14	Control	77.6	2,152	10.5	0	1.6	13.8
		500	73.2	2,419	13.4	0	2.3	16.0
		700	75.5	2,560	16.5	0	2.7	18.6
	21	Control	77.3	2,401	13.2	2.2	2.0	11.9
		500	75.0	2,884	20.3	5.3	5.3	22.5
		700	73.7	3,049	21.3	5.4	5.3	29.4

[a] Photosynthetic rate : $\mu mol\ m^{-2}\ s^{-1}$, [b] Control : 350 ppm

ering stage as the CO_2 concentration increased, but showed no big difference between the 500 and 700 ppm group. Photosynthetic rate increased as the CO_2 concentration increased.

The plant height of Taekwang under the 500 and 700 ppm treatment groups were longer than control group at around the 7th day after the treatment, but from the 14th day onward, longest plant height was observed under the control group. Leaf area showed big increase as the CO_2 treatment period and concentration increased, showing big difference in top dry weight. The pods of Taekwang developed a little later than Cheongja on the 21st day after treatment and the pod weight increased in the 500 and 700 ppm treatment groups relative to the control group. Root dry weight of Taekwang and Cheongja increased as the CO_2 concentration increased. Photosynthetic rate of both varieties increased as CO_2 level increased.

Allen *et al.* (1991) treated CO_2 from 160 to 660 mmol/mol and found out that soybean dry weight increased from 12.88 to 39.12 g per plant, and grain weight increased from 5.77 to 17.85 g. Jones *et al.* (1984) reported that under the CO_2 concentration of 330 and 800 mmol/mol, the maximum photosynthetic rate of the soybean was recorded at 70 days after sowing and was 60 and 90 mmol $CO_2/m^2/s$, respectively, and leaf area index was 6.9 and 9.0, respectively, indicating that increased CO_2 resulted in increased photosynthetic rate. Moreover, under the CO_2 concentration of 320 and 640 mmol/mol, the maximum photosynthetic rate was 40 and 75 $mmol/m^2/s$, respectively (Jones *et al.*, 1985c), and under the CO_2 concentration of 330 and 800 $mmol/m^2/s$, the maximum photosynthetic rate was 40 and 80 $mmol/m^2/s$, respectively(Jones *et al.*, 1985a, b).

Valle *et al.* (1985) reported that under the CO_2 concentration of 330 and 660 m mol/mol, soybean leaf showed maximum photosynthetic rate of 30 - 50 $mmol/m^2/s$. Allen *et al.* (1990) reported that as the CO_2 concentration increased from 330 to 800 mmol/mol, photosynthetic rate increased in all soybean leaves. Campbell *et al.* (1990) reported that photosynthetic rate was higher in 330 than 660m mol/mol of CO_2 concentration.

The relationship between soybean nodules and CO_2 concentration is shown in Fig. 2. Both Cheongja and Taekwang showed increased nodules as the treatment period lengthened and CO_2 concentration increased.

Under enriched CO_2, the assimilation rate caused the growth and yield of soybeans. Over time, however, the increase in overall leaf area and dry weight diminished, resulting from the reduced carbon usage rate for reproduction. Davey *et al.* (1999) reported that the photosynthetic

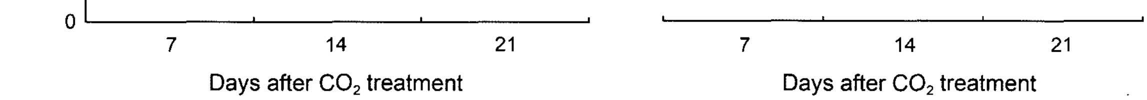

Fig. 2. Changes of nodule number according to the days after treatment of different CO_2 concentrations at R1 stage.

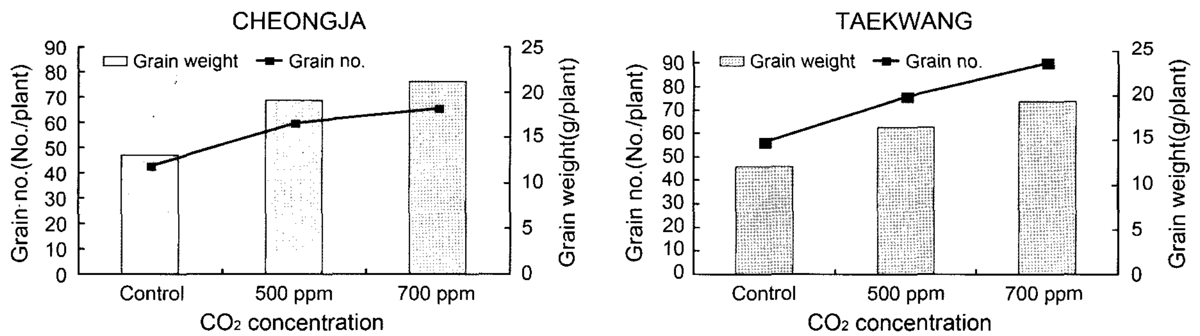

Fig. 3. Changes in grain yield of soybean according to the concentration of CO_2 at maturity stage.

stimulation of the nitrogen-fixing varieties grown under enriched CO_2 was three times as high as that of the non-nodule varieties. Nodule varieties are supposed to have an added factor of accumulating carbohydrates compared to non-nodule varieties. This added factor will depend on environment, but respiration rate of nodule soybeans played more important role than sound root tissue (Vessey *et al.*, 1988).

Yield Responses

The effects of CO_2 treatment on the grain yield of two soybean varieties were analyzed after the CO_2 treatment from the blooming to the harvesting stage. As shown in Fig. 3, both Cheongja and Taekwang produced more grain yield in the 500 and 700 ppm treatment groups than the control group, resulting in higher grain weight.

Kimball (1983) reported that soybean yield increased by 24% under the elevated CO_2 concentration. This result was a little lower than the 33% average increase based on the 430 researches on the crops and CO_2, and even lower than the 40% increase as reported by Conroy *et al.* (1994).

The grain yield per plant under the 500 and 700 ppm treatment increased compared to the control group. However, CO_2 increase during the blooming stage is considered to promote the aging of the plant.

Correlation of Photosynthetic Rate, Stomatal Conductance, and Transpiration Rate According to CO_2 Concentration

Changes in photosynthetic rate and stomatal conductance according to the CO_2 concentration are shown in Fig. 4. In relation to increased photosynthetic rate, stomatal conductance appeared lower in the high CO_2 concentration treatments than those in low concentration treatments. When atmospheric CO_2 rose, most crops responded with lower transpiration per leaf area. Hence, stomatal conductance decreased while leaf area index rose. Under doubled CO_2 concentration, reports show that a 40% decrease in stomatal conductance results to less than 10% decrease in water usage of the crops in chambers or experimental wrappings. In terms of transpiration rate change of the crops, crop energy balance is adjusted by the stomatal conductance, leaf area index, crop structures and climate factors (Allen, 1996).

The correlation between photosynthetic rate and transpiration rate according to the CO_2 concentration is shown in Fig. 5. Results show that as photosynthetic rate rises, so does transpiration rate. In relation to photosynthetic rate increment, transpiration rate appeared higher in the lower levels of CO_2 than in the higher ones. Allen *et al.* (1985) reported that beans grown under enriched CO_2 showed higher water use efficiency as affected by increased photosynthesis than that affected by decreased respiration. Besides, the increase in water use efficiency due to increased photosynthesis and decreased respiration was 0.8 and 0.2, respectively (Jones *et al.*, 1985b). The report also mentioned that increased water use efficiency under elevated CO_2 levels resulted more from increased photosynthesis than from decreased water loss by partial closure of stomata (Allen, 1996). Rice showed similar trend (Kim *et al.*, 2005). Widodo *et al.* (2003) experimented rice water content and cold stress damage under the CO_2 levels of 350 and 700 ppm over its whole growth period and found out that drought treatment effect was more severe in the plants grown in the natural environment than those under CO_2 treatment. Besides, rice under elevated

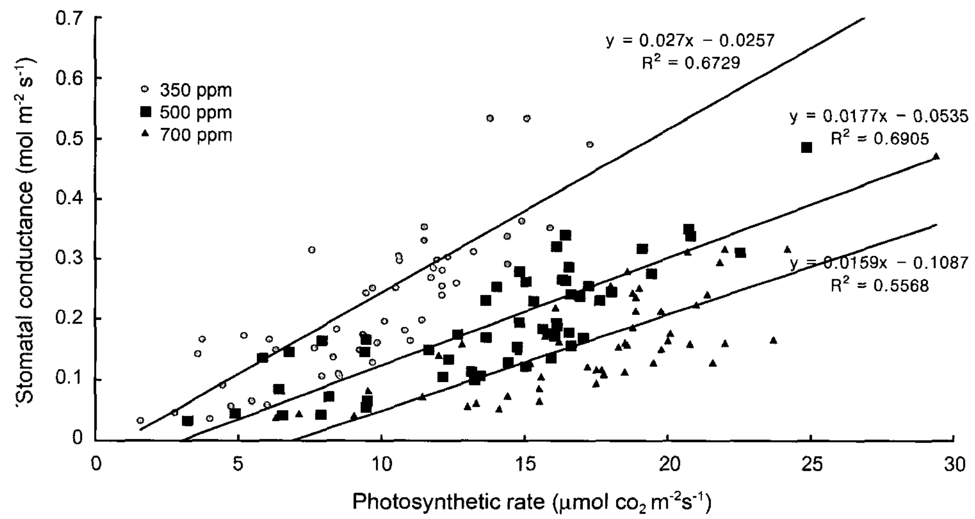

Fig. 4. Changes in photosynthetic rate and stomatal conductance according to the concentration of carbon dioxide.

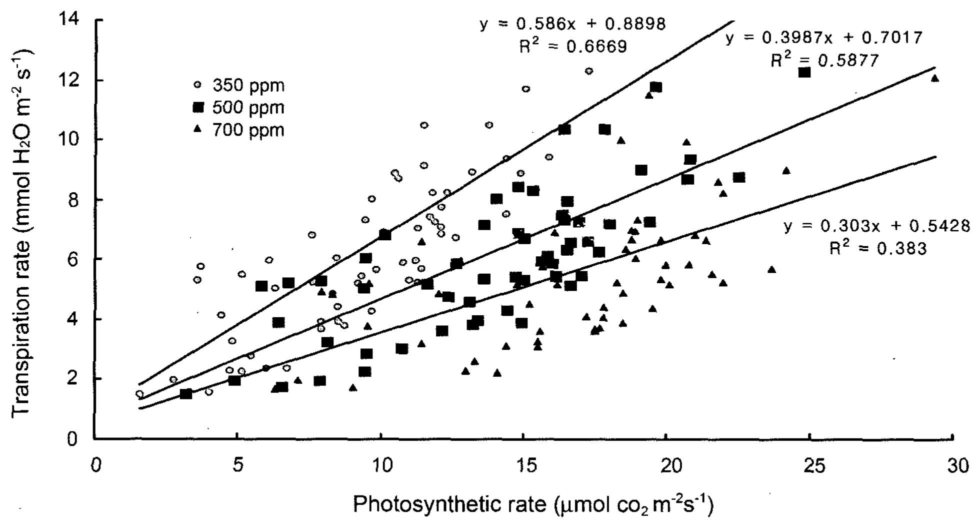

Fig. 5. Changes in photosynthetic rate and transpiration rate according to the concentration of carbon dioxide.

CO_2 showed increased photosynthetic rate during the day, wider photosynthesis-related variables, longer drought-enduring period, and faster recovery. These research results indicate that beans grown in areas with higher atmospheric CO_2 content will perform better during drought periods. But as CO_2 level increase ensues, atmospheric temperature rise, and water use efficiency can decrease.

CONCLUSION

The experiment observed the growth and photosynthesis-related responses of soybeans under the elevated atmospheric CO_2 level. Results showed that:

The germination rate of Taekwang and Cheongja soybeans under enriched CO_2 was over 93% around the 7th day from sowing, and therefore showed not much difference between the different CO_2 concentrations. At the V2 stage CO_2 treatment, CO_2 concentration showed positive relationship with leaf area, top dry weight, and photosynthetic rate, but root dry weight showed insignificant differences. At the blooming stage CO_2 treatment, CO_2 concentration showed positive relationship with leaf area, top dry weight, and photosynthetic rate. Pod weight and nodules of the roots increased in the 500 and 700 ppm CO_2 treatment groups. The grain weight and yield per plant of Cheongja and Taekwang increased under the elevated CO_2 concentration. CO_2 concentration is negatively related to stomatal conductance and transpiration rate, resulting in high water use efficiency.

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