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Variable Responses to CO_2 of the Duration of Vegetative Growth and Yield within a Maturity Group in Soybeans

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Abstract

Prior experiments in indoor chambers and in the field using free-air carbon dioxide enrichment (FACE) systems indicated variation among soybean cultivars in whether and how much elevated CO_2 prolonged vegetative development. However, the cultivars tested differed in maturity group, and it is not known whether variation exists in CO_2 effects on the duration of vegetative growth within a maturity group. In these experiments, a total of five soybean cultivars of maturity group IV were grown at ambient and elevated CO_2 in the field in Maryland, USA using FACE systems, over three years. The time of first flowering, the time of the first open flowers at the apex of the main stem, the total number of main stem nodes at maturity, and seed yield were recorded. In each year of the study, there were cultivars in which elevated CO_2 did not affect the duration of vegetative growth or the main stem node number, and other cultivars in which elevated CO_2 prolonged vegetative growth and increased the number of main stem nodes and seed yield at maturity. The stimulation in yield by elevated CO_2 was highly correlated with the increase in the number of main stem nodes, indicating that CO_2 effects on the duration of vegetative growth may be important in adapting soybean to higher atmospheric CO_2.

Keywords

Soybean, Elevated CO_2, Yield, Flowering

1. Introduction

Seed yield increases of soybeans in response to increases in CO_2 concentration of 180 to 200 $\mu mol \cdot mol^{-1}$ above the current ambient concentration applied using free air carbon dioxide enrichment (FACE) systems have ranged from about 0% to 45% in different cultivars [1]-[5]. Reasons for the wide range of responses among cultivars at the same location remain unclear. Delay in the transition from vegetative to reproductive growth in response to elevated CO_2 varied among cultivars and was highly correlated with the seed yield increase both in indoor chambers and in field FACE systems [3]. Delayed transition to reproductive growth increased main stem and axillary node number, providing more sites for pods, and increasing seed yield. However, the cultivars compared in that study varied in maturity group, and it is not known whether variation exists within a soybean maturity group in effects of elevated CO_2 on the duration of vegetative growth, or whether any such variation would be correlated with yield increase. Soybean cultivars used in North America have been assigned to "maturity groups" in order to specify the latitudinal band best suited to that cultivar. Reproductive development in soybean is affected by both photoperiod and temperature.

2. Materials and Methods

Experiments were conducted in 2013, 2014, and 2015 at the South Farm of the Beltsville Agricultural Research Center, Beltsville, Maryland, using maturity group IV cultivars adapted to the local conditions. Among the five cultivars used, Clark, Corsica, Kent, Spencer and Stress land, two or three cultivars were grown in each year, with Spencer grown every year (**Table 1**). The field site (39˚02'N, 76˚94'W, elevation 30 m) is on a flood plain with a Codorus silt loam soil, a fine-loamy, mixed, mesic Fluvaquentic Dystrochrept.

There were three plots with elevated CO_2 and three plots with no CO_2 added each year. Each plot covered 12 m^2 and was equally divided among the two or three cultivars. The row width was 30 cm, and seedlings were thinned to an overall density of 40 plants per m^2. Plots were tilled just prior to planting, and CO_2 addition began before seed emergence. The plots had been fertilized with N, P and K for the prior winter wheat crop at locally recommended rates, but no fertilizer was applied to the soybean crops. The plots were not irrigated, but no severe water stress occurred in any of these years, because precipitation was near normal.

Elevated CO_2 was applied continuously from planting using area distributed FACE systems [4]. The control system was set for a daytime CO_2 elevation of 190 $\mu mol \cdot mol^{-1}$ above the ambient concentration, and 220 $\mu mol \cdot mol^{-1}$ above ambient at night. Whole season mean concentrations were 455 $\mu mol \cdot mol^{-1}$ for the ambient plots and 663 $\mu mol \cdot mol^{-1}$ for the elevated plots, averaged over the three seasons. Midday ambient CO_2 concentration averaged 384 $\mu mol \cdot mol^{-1}$. One minute averages of CO_2 concentration in the ele-

Table 1. Planting times and cultivars grown in each year of the experiment.

Year	Cultivars	Planting (Day of Year)
2013	Clark, Spencer	176
2014	Clark, Kent, Spencer	180
2015	Corsica, Spencer, Stressland	176

vated plots were within 10% of the target concentration 86% of the time during the daytime, and 73% of the time at night. Ambient CO_2 concentrations at night were higher at low wind speeds, and ranged from about 400 to over 600 μmol·mol^{-1}.

Within each plot 3 to 5 representative individual plants of each cultivar were tagged before flowering and the day of year when they reached the R1 stage of flowering (first open flower anywhere on the plant, [6]), the day of year when the first open flower occurred at the apex of the main stem, and the total number of main stem nodes at maturity were recorded for each tagged plant. Mean values for each plot were used to compare the ambient and elevated CO_2 plots for each cultivar, using ANOVA, with n = 3 replicate plots per treatment. Interactions between CO_2 treatment and cultivar were tested using split-plot ANOVA.

At crop maturity in 2013 and 2014, 4 m of an interior row was harvested for each cultivar and plot for determination of seed yield. In 2015, weed control was not adequate to prevent reductions in crop yield by weeds, so yields were not obtained for that season.

3. Results and Discussion

The effect of the elevated CO_2 treatment was to delay R1, delay flowering at the apex, and to increase the number of main stem nodes, or to have no effect on these parameters, depending on the cultivar. Thus elevated CO_2 either prolonged vegetative growth or had no effect on its duration. Elevated CO_2 never accelerated either vegetative or reproductive development in these field experiments, as also found by Castro *et al*. [7]. No increase in the rate of main stem node production at elevated CO_2 was also found in indoor chambers with a wide range of day lengths [8]. In each year of this field study there were CO_2 effects on the date of flowering at the apex, and on the number of main stem nodes at maturity for at least one cultivar, and no effects in other cultivar (s). This led to significant cultivar × CO_2 interactions for both of these parameters in each year (Table 2). CO_2 effects on the date of R1 were less consistent, and did not always occur even in cases in which the date of flowering at the apex and main stem node number

Table 2. Day of year (DOY) for reaching the R1 stage of development and for the first open flower at the apex of the main stem, the number of main stem nodes at maturity, and the probability of a CO_2 × cultivar interaction for each year of the experiment.

Year	Cultivar	DOY for R1		DOY for Apex		Nodes		Prob. of CO_2 × Cultivar		
		Amb	Elev	Amb	Elev	Amb	Elev	R1	Apex	Nodes
2013	Clark	212	213	237	237	17.1	17.3	0.350	0.013	0.037
	Spencer	212	211	238	241*	16.3	18.0*			
2014	Clark	222	222	237	237	14.2	14.3	0.023	0.047	0.037
	Kent	225	228*	244	247*	16.5	18.1*			
	Spencer	220	222*	234	236*	14.7	15.4*			
2015	Corsica	191	191	215	215	20.1	19.7	0.046	0.033	0.022
	Spencer	194	196*	215	219*	20.4	22.6*			
	Stressland	195	195	219	219	21.7	21.5			

*indicates a significant effect of CO_2 treatment for that cultivar in that year at P = 0.05.

were affected (**Table 2**). Prior work also indicated no fixed relationship between CO_2 effects on the date of R1 and on the duration of vegetative growth among soybean cultivars of different maturity groups [3]. Delays in the date of flowering at the apex and increases in the number of main stem nodes caused by elevated CO_2 occurred for the cultivar Spencer in each of the three years. In these studies all cultivars reached maturity at least a week before the first frost occurred in the fall, even at elevated CO_2.

There are at least four genes affecting the photoperiodic control of flowering in soybean [9]. Studies using near isogenic lines for three of these genes indicated that each of those three genes influenced how elevated CO_2 affected flowering time at some photoperiod [8]. There is considerable variation in the timing of flowering stages within maturity groups under natural photoperiods, presumably related to differences in photoperiod sensitive genes, so it is not surprising that variation exists within a maturity group in CO_2 effects on the duration of vegetative growth.

The ratio of seed yield at elevated to that at ambient CO_2 for each cultivar increased approximately linearly with the increase in the main stem node number caused by growth at elevated CO_2 (**Figure 1**). Also shown in **Figure 1** are data for two cultivars not of maturity group IV previously described [3]. This correlation between the yield ratio and the increase in the number of main stem nodes is probably consistent with the observation of Bishop *et al.* [1] that the two soybean cultivars with the largest relative yield increase at elevated CO_2 (Loda and Dwight) also had the largest delay in reaching maturity at elevated CO_2, although main stem node numbers were not presented. Increases in main stem node number in response to elevated CO_2 have also been found in other soybean studies at Soy FACE [7] [10]. Rising temperatures may prevent delayed maturity induced by elevated CO_2 in some cultivars from resulting in yield losses due to low temperatures occurring before crop maturation. For example, no yield losses due to delayed maturity at elevated CO_2 occurred in this three-year study. CO_2 effects on the

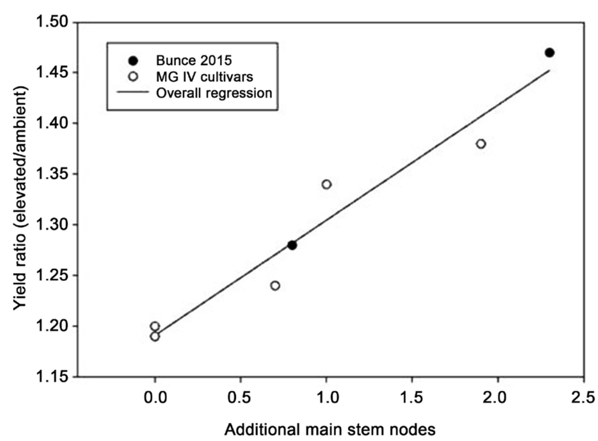

Figure 1. The ratio of yield at elevated to ambient CO_2 in relation to the additional number of main stem nodes at maturity at elevated CO_2. Open symbols are for maturity group IV soybean cultivars, years 2013 and 2014. Closed symbols are for two other cultivars reported in bunce (2015) [3] of different maturity groups. The overall regression had $r^2 = 0.948$.

duration of vegetative growth may be important in adapting soybean to higher atmospheric CO_2, and this study indicates that variation in this CO_2 response exists within a maturity group.

4. Conclusion

Variable effects of elevated CO_2 on flowering occurred within a single maturity group, as evidenced by the fact that for each year of this study, there were cultivars in which elevated CO_2 did not affect the duration of vegetative growth or the main stem node number, and other cultivars in which elevated CO_2 prolonged vegetative growth and increased the number of main stem nodes and seed yield at maturity. The stimulation in yield by elevated CO_2 was highly correlated with the increase in the number of main stem nodes, indicating that CO_2 effects on the duration of vegetative growth may be important in adapting soybean to higher atmospheric CO_2.

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