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# Effects of Atmospheric $CO_2$ Enrichment on Crop Nutrient Dynamics under No-Till Conditions

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## ABSTRACT

Increasing atmospheric $CO_2$ concentration could increase crop productivity and alter crop nutrient dynamics. This study was conducted (3 yrs) with two crops ([*Glycine max* (L.) Merr.] and grain sorghum [*Sorghum bicolor* (L.) Moench.]) grown under two $CO_2$ levels (ambient and twice ambient) using open top field chambers on a Blanton loamy sand under no-tillage. Macronutrient and micronutrient concentrations and contents were determined for grain, stover, and roots. Although elevated $CO_2$ tended to reduce nutrient concentrations, high $CO_2$ consistently increased nutrient content especially in grain tissue; this response pattern was more notable with macronutrients. The $CO_2$ effect was observed primarily in soybean. The consistent $CO_2$-induced increases in grain macronutrient contents favors reliable predictions of system outputs, however, predictions of crop nutrient inputs (i.e., stover and root contents) to the soil are less robust due to observed variability. Again, this is particularly true in regards to micronutrient dynamics in $CO_2$-enriched cropping systems.

**Keywords:** elevated $CO_2$, conservation tillage, soybean, sorghum, macronutrients, micronutrients

## INTRODUCTION

Fossil fuel consumption and land use changes associated with industrial and/or population expansion have contributed significantly to the global rise in atmospheric $CO_2$ concentration (Keeling and Whorf, 1994). This rise in atmospheric $CO_2$ may impact highly managed agricultural systems since $CO_2$ is a primary input for crop growth. Over the last decade, numerous studies have demonstrated

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that elevated atmospheric $CO_2$ often enhances plant water use efficiency, net photosynthesis, and biomass production (Kimball, 1983; Rogers and Dahlman, 1993; Amthor, 1995; Kimball, Kobayashi, and Bindi, 2002).

Greater biomass production due to elevated $CO_2$ could impact cropping systems, especially those employing conservation tillage management. Reduced soil tillage in combination with $CO_2$-induced increases in non-yield residues (above- and belowground) could increase both soil C storage and ground coverage, improve soil physical properties, and possibly reduce soil erosion. Further, enhancements in grain and non-yield residues may be significant to nutrient management since these components represent, respectively, nutrient outputs and inputs for cropping systems. The key role of nutrients in our changing global C cycle must be elucidated if we are to predict how this change will impact agroecosystem function.

Nutrient supplies are critical to plant systems and attenuate the dynamic flows of essential materials (e.g., carbon and water) through them. The concentration of nutrients in plant tissues is largely influenced by roots, as these are the primary mechanism for extraction of nutrients from soil; therefore, positive effects of $CO_2$ on roots will affect whole plant nutrition. Whole plant nutrient uptake (or content) is increased for many species under elevated $CO_2$, but the concentration of most nutrients on a per unit weight of tissue basis declines. Elevated atmospheric $CO_2$ usually increases the size of plants and their component parts, resulting in greater total amounts of nutrients, but these nutrients are distributed throughout the larger plants thus diluting the concentration per unit weight. Results on nutrient uptake and concentration can often vary due to differences in nutritional levels applied during the course of the experiments (Conroy, 1992; Linder and McDonald, 1993). Reviews of the literature have shown that, under elevated $CO_2$, plant nutrient content and nutrient use efficiency are generally increased while nutrient tissue concentration and nutrient uptake efficiency often decline (Rogers, Runion, and Krupa, 1994; Rogers et al., 1999). However, it is important to note that many of the reviewed studies were not conducted in the field and often assessed green tissue, which may not be reflective of senesced plant material more common to field situations (Amthor, 1995).

More $CO_2$ research with $C_3$ and $C_4$ crops grown concurrently under the same experimental conditions is needed; these two photosynthetic types are known to respond differentially to elevated $CO_2$ both with regard to carbon metabolism and water use. This difference in response could become important with regard to future management decisions. In the current study, soybean (a $C_3$ crop) and sorghum (a $C_4$ crop) were managed under two atmospheric $CO_2$ concentrations; ambient and twice-ambient $CO_2$ levels were selected since atmospheric $CO_2$ may double within the next 100 yr (Keeling and Whorf, 1994). This design offered the opportunity to make a direct statistical comparison of $C_3$ and $C_4$ crops over a multi-year period. The objective was to investigate the effects of increased $CO_2$ level on nutrient concentration and content of grain and non-yield residues produced by $C_3$ and $C_4$ crops grown under no-tillage conditions.

## MATERIALS AND METHODS

Soybean ('Stonewall') and grain sorghum ('Savanna 5') plants were grown from seed to maturity in open top field chambers (Rogers, Heck, and Heagle, 1983) at two atmospheric $CO_2$ concentrations (ambient = 360 $\mu$ll$^{-1}$ and twice ambient = 720 $\mu$ll$^{-1}$) on a soil bin (2 m deep, 6 m wide, and 76 m long) located at the USDA-ARS National Soil Dynamics Laboratory, Auburn, AL (Batchelor, 1984). The bin contained a Blanton loamy sand (loamy, siliceous, thermic Grossarenic Paleudult) that had been fallow (>25 years) prior to study initiation.

For three seasons, plants were grown as described above and managed under no-till conditions. Soybean seeds were inoculated with commercial Rhizobium prior to planting. Plants were thinned to a final density of 30 or 26 plants m$^{-2}$ for soybean and sorghum, respectively. For adequate plant establishment, fertilizer N was broadcast at a rate of 34 kg N ha$^{-1}$ shortly after planting. For sorghum, an additional 67 kg N ha$^{-1}$ was applied 30 days after planting. Weed control was done by hand and/or by use of glyphosate during both the growing season and overwintering period between seasons.

Plants within each chamber (3 m diameter) were harvested at maturity for dry mass production (stover) and grain yield as previously reported (Prior et al., 1997, 2004). Biomass subsamples were oven dried (55°C) and weighed; remaining plant stalks were cut with hedge clippers (15 cm lengths) and returned to plots. Aboveground material, including 10% (by weight) of the grain yield, was returned to study plots to simulate normal farm operations. Chambers were then removed, but their locations remained fixed and delineated by a permanent 3-m aluminum ring. Bird netting (1.6 cm by 1.9 cm openings) was placed over the soil bin to prevent movement of residue into or out of the plots during the overwintering period. In addition, estimates of the root system, as previously reported by Prior et al. (2003), were based on soil core and root extraction techniques (Prior and Rogers, 1992; Prior et al., 1995). Twelve root-soil cores (2.4 cm diameter, 30 cm length) were collected from each chamber; roots were separated from soil with a hydropneumatic elutriation system (Smucker, McBurney, and Srivastava, 1982). After organic debris had been removed with tweezers and spring-loaded suction pipettes, root weight determinations (55°C) were made. The root extraction technique used a manual winch mounted onto a tripod with a cable gripping tool attached to the plant stalk to break the roots from the soil (12–16 plants per chamber). Roots were washed free of soil using a soft bristle brush prior to dry weight determination (55°C). Root dry weights from each root sampling method were expressed on an area basis prior to being combined.

The biomass material was ground (0.2 mm mesh) prior to nutrient analysis. Nitrogen was determined with a LECO CHN-600 analyzer (LECO Corp., Augusta, GA). In addition, subsamples of plant parts were heated in a muffle furnace for 4.5 hr at 450°C (Hue and Evans, 1986). The resulting ash was then dissolved in 1 M $HNO_3$ and 1 M HCl, successively; primary (P and K) and secondary (Ca and Mg) nutrients along with micronutrients (Cu, Fe, Mn, and Zn) were then measured by inductively coupled plasma spectrophotometry (ICP 9000, Thermo Jarell-Ash Corp., Franklin, MA). Nutrient concentration and content were determined for grain, stover (aboveground non-yield components), and roots.

The study was a split-plot design with three blocks. Whole-plot treatments (crop) were randomly assigned to half of each block; subplot treatments ($CO_2$) were randomly assigned to two chambers within each whole-plot. Statistical analyses were done using the Mixed procedure of the Statistical Analysis System (Littell et al., 1996). A significance level of $P \leq 0.10$ was established *a priori*.

## RESULTS

### Grain

Grain N, P, K, Ca, and Mg concentrations were lower in sorghum than soybean (Table 1). Nitrogen concentrations were lower under high $CO_2$ for both crops in 1992 and 1994; this effect was also true for Mg concentration in 1992. Growth under elevated $CO_2$ resulted in significantly lower soybean grain K and Ca concentration only in 1992 and $CO_2$ level had no affect on P concentration across all years.

For both primary (N, P, and K) and secondary (Ca and Mg) nutrients, soybean grain nutrient contents were generally higher than sorghum across years (Table 1). In addition, elevated $CO_2$ increased grain N, P, K, Ca, and Mg content for the soybean crop in all years. Although the general trend was for higher content values for soybean, elevated $CO_2$ did lead to some significant smaller increases for sorghum in 1992 (i.e., for P and Mg) and 1993 (i.e., N).

Evaluation of micronutrient concentrations in grain tissue indicated sorghum was always significantly lower in Mn and Zn compared to soybean in all years (Table 2). No differences in grain Fe and Cu concentrations were observed between crops. The only observed effect of $CO_2$ treatment occurred for sorghum Fe concentration in 1992.

Micronutrient differences between crops were limited to Mn content across all years and Zn content in 1994. In these cases, contents for sorghum were lower than corresponding values for soybean (Table 2). Significant $CO_2$ by crop species interactions indicated that growth under elevated $CO_2$ resulted in significantly higher grain contents for Mn (all years) and Zn (1993 and 1994) in soybean; elevated $CO_2$ did lead to a smaller significant increase for sorghum

Table 1

Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) grain macronutrient concentrations (g kg$^{-1}$) and contents (g m$^{-2}$) for soybean (SB) and sorghum (SG) grown under ambient (360) and twice ambient (720) $CO_2$ conditions for three growing seasons (1992–1994)

| | 1992 | | | | | 1993 | | | | | 1994 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc. | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| SB-360 | 63.45 | 3.89 | 17.21 | 2.58 | 2.19 | 71.17 | 3.56 | 12.73 | 2.78 | 2.15 | 74.27 | 3.85 | 13.91 | 2.32 | 1.64 |
| SB-720 | 60.96 | 3.76 | 16.79 | 2.71 | 2.10 | 71.02 | 4.82 | 17.46 | 2.56 | 2.01 | 70.55 | 4.01 | 13.67 | 1.21 | 1.65 |
| SG-360 | 13.49 | 2.48 | 3.35 | 0.24 | 1.24 | 15.14 | 1.73 | 2.42 | 0.27 | 1.28 | 15.79 | 2.33 | 2.61 | 0.16 | 1.04 |
| SG-720 | 11.11 | 2.46 | 3.39 | 0.25 | 1.18 | 15.16 | 2.35 | 3.32 | 0.30 | 1.19 | 12.78 | 2.21 | 2.59 | 0.18 | 1.00 |
| Pr>F* | | | | | | | | | | | | | | | |
| $CO_2$ | 0.008 | 0.410 | 0.113 | 0.048 | 0.043 | 0.934 | 0.284 | 0.337 | 0.201 | 0.237 | 0.001 | 0.799 | 0.351 | 0.228 | 0.765 |
| Spp | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.033 | 0.004 | <0.0001 | <0.0001 | <0.0001 | 0.004 | <0.0001 | <0.0001 | <0.0001 |
| $CO_2$ x Spp | 0.944 | 0.512 | 0.072 | 0.079 | 0.648 | 0.917 | 0.713 | 0.505 | 0.117 | 0.793 | 0.593 | 0.120 | 0.433 | 0.087 | 0.412 |
| Content | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| SB-360 | 15.87 | 0.97 | 4.31 | 0.64 | 0.55 | 11.54 | 0.57 | 2.02 | 0.45 | 0.35 | 13.17 | 0.68 | 2.47 | 0.41 | 0.29 |
| SB-720 | 20.57 | 1.27 | 5.67 | 0.91 | 0.71 | 19.20 | 1.31 | 4.73 | 0.69 | 0.55 | 17.48 | 0.99 | 3.39 | 0.55 | 0.41 |
| SG-360 | 5.14 | 0.94 | 1.28 | 0.09 | 0.47 | 5.88 | 0.67 | 0.95 | 0.11 | 0.50 | 3.09 | 0.45 | 0.51 | 0.03 | 0.20 |
| SG-720 | 4.96 | 1.10 | 1.51 | 0.11 | 0.53 | 6.76 | 1.05 | 1.48 | 0.13 | 0.53 | 2.09 | 0.48 | 0.57 | 0.04 | 0.22 |
| Pr>F | | | | | | | | | | | | | | | |
| $CO_2$ | 0.002 | 0.001 | 0.0003 | 0.0001 | 0.001 | <0.0001 | 0.025 | 0.015 | 0.002 | 0.018 | 0.002 | 0.001 | 0.001 | 0.001 | 0.002 |
| Spp | <0.0001 | 0.022 | <0.0001 | 0.0003 | 0.0003 | 0.002 | 0.678 | 0.004 | 0.003 | 0.146 | <0.0001 | 0.015 | <0.0001 | <0.0001 | 0.001 |
| $CO_2$ x Spp | 0.002 | 0.087 | 0.002 | 0.0002 | 0.022 | <0.0001 | 0.378 | 0.066 | 0.004 | 0.051 | 0.001 | 0.001 | 0.002 | 0.001 | 0.001 |

*Significance levels from the mixed models procedure of SAS.

Table 2

Copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) grain micronutrient concentrations (mg kg$^{-1}$) and contents (mg m$^{-2}$) for soybean (SB) and sorghum (SG) grown under ambient (360) and twice ambient (720) $CO_2$ conditions for three growing seasons (1992–1994)

| | 1992 | | | | 1993 | | | | 1994 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc. | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn |
| SB-360 | 5.74 | 39.19 | 66.75 | 40.08 | 6.66 | 36.85 | 68.62 | 48.78 | 5.38 | 108.49 | 42.30 | 41.30 |
| SB-720 | 5.00 | 39.21 | 65.67 | 38.24 | 6.66 | 25.15 | 64.38 | 46.22 | 4.95 | 101.47 | 42.44 | 40.35 |
| SG-360 | 3.52 | 11.12 | 26.60 | 23.12 | 2.22 | 14.63 | 24.02 | 22.51 | 4.52 | 89.27 | 14.96 | 21.12 |
| SG-720 | 13.20 | 48.56 | 24.97 | 24.27 | 3.71 | 20.49 | 23.13 | 23.29 | 4.52 | 105.02 | 13.70 | 19.66 |
| Pr>F* | | | | | | | | | | | | |
| $CO_2$ | 0.345 | 0.091 | 0.233 | 0.862 | 0.205 | 0.701 | 0.359 | 0.445 | 0.372 | 0.795 | 0.457 | 0.493 |
| Spp | 0.526 | 0.391 | <0.0001 | 0.018 | 0.017 | 0.113 | <0.0001 | 0.003 | 0.422 | 0.760 | <0.0001 | <0.0001 |
| $CO_2$ x Spp | 0.282 | 0.091 | 0.801 | 0.469 | 0.203 | 0.271 | 0.541 | 0.187 | 0.375 | 0.508 | 0.365 | 0.883 |
| Content | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn |
| SB-360 | 1.44 | 9.781 | 16.69 | 10.03 | 1.08 | 6.06 | 11.09 | 7.92 | 0.95 | 19.16 | 7.50 | 7.31 |
| SB-720 | 1.69 | 13.250 | 22.15 | 12.91 | 1.80 | 6.70 | 17.41 | 12.52 | 1.22 | 25.09 | 10.53 | 10.00 |
| SG-360 | 1.34 | 4.17 | 10.09 | 8.80 | 0.86 | 5.65 | 9.33 | 8.76 | 0.88 | 17.45 | 2.92 | 4.11 |
| SG-720 | 6.10 | 21.64 | 11.16 | 10.92 | 1.67 | 9.37 | 10.28 | 10.37 | 0.99 | 21.96 | 2.98 | 4.26 |
| Pr>F | | | | | | | | | | | | |
| $CO_2$ | 0.278 | 0.047 | <0.0001 | 0.077 | 0.013 | 0.423 | 0.001 | 0.001 | 0.026 | 0.101 | 0.001 | 0.003 |
| Spp | 0.353 | 0.780 | <0.0001 | 0.294 | 0.487 | 0.672 | 0.0003 | 0.358 | 0.236 | 0.572 | 0.0001 | <0.0001 |
| $CO_2$ x Spp | 0.323 | 0.131 | 0.001 | 0.741 | 0.864 | 0.567 | 0.004 | 0.011 | 0.202 | 0.788 | 0.002 | 0.005 |

*Significance levels from the mixed models procedure of SAS.

Zn content in 1993. Significant main effects of $CO_2$ indicated that Cu (1993 and 1994), Fe (1992 and 1994), Zn contents (1992) were higher under elevated $CO_2$.

## STOVER

Stover N, P, Ca, and Mg concentrations generally were lower in sorghum than soybean. Sorghum and soybean stover K concentrations were similar except for the higher sorghum values noted in 1994 (Table 3). Nitrogen concentrations tended to be lower under high $CO_2$ across years, while P concentration was only impacted by high $CO_2$ in 1992. Growth under elevated $CO_2$ resulted in significantly lower K concentrations in soybean in both 1993 and 1994; a smaller $CO_2$ affect was noted for sorghum in 1994. Significant main effects of $CO_2$ indicated that Ca concentrations were lower under high $CO_2$ in 1992 and 1994; this was also true for Mg concentration in 1994 with a similar trend noted in 1992. In 1993, elevated $CO_2$ lowered Mg concentration in soybean only.

Differences in stover N, P, and K contents were observed between crops except for K in 1992 and P in 1993; similar differences were also noted for Ca and Mg contents except for Ca in 1993 (Table 3). In this case, contents for soybean were generally higher than the sorghum crop. Elevated $CO_2$ increased stover N content for soybean in 1992 and 1993. Although only significant in 1993, a similar $CO_2$ effect was also noted for P content in the other two years. Growth under elevated $CO_2$ resulted in significantly higher stover contents for K (1993 and 1994) and Mg (1993) in soybean; a smaller $CO_2$ effect was noted for sorghum K and Mg contents in 1993. Significant main effects of $CO_2$ indicated that Ca content was higher under elevated $CO_2$ in 1993, however, in the other years (1992 and 1994), elevated $CO_2$ led to increases in Ca content in soybean only.

Unlike grain tissue, micronutrient concentrations in stover tissue indicated sorghum was always significantly higher in Mn and Zn compared to soybean in all years (Table 4); stover Cu concentrations for sorghum were also higher than soybean in two of three years (1992 and 1993). As observed with grain tissue, no differences in stover Fe concentrations between crops were observed. Significant $CO_2$ by crop species interactions were noted for stover Mn (1992 and 1994) and Zn (1992) concentrations; these micronutrients were lowered by elevated $CO_2$ in sorghum stover only.

Evaluation of micronutrient content in stover tissue indicated that all sorghum values were significantly higher than soybean in all years with the one exception of Fe content in 1993 (Table 4). Significant main effects of $CO_2$ indicated that stover Cu (1994), Mn (1993), Zn contents (1994) were higher under elevated $CO_2$; a similar trend was noted for Zn content in 1992. Significant $CO_2$ by crop species interactions indicated that growth under elevated $CO_2$ resulted in significantly higher stover contents of Mn (1992) and Zn (1993) in

Table 3

Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) stover macronutrient concentrations (g kg$^{-1}$) and contents (g m$^{-2}$) for soybean (SB) and sorghum (SG) grown under ambient (360) and twice ambient (720) $CO_2$ conditions for three growing seasons (1992–1994)

| | 1992 | | | | | 1993 | | | | | 1994 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc. | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| SB-360 | 14.00 | 0.70 | 12.53 | 7.25 | 3.07 | 15.70 | 1.17 | 11.37 | 6.71 | 3.51 | 14.40 | 0.61 | 5.03 | 3.83 | 1.78 |
| SB-720 | 12.20 | 0.60 | 9.74 | 6.83 | 2.62 | 15.03 | 1.01 | 7.48 | 6.38 | 3.15 | 8.68 | 0.50 | 2.51 | 3.47 | 1.41 |
| SG-360 | 5.37 | 0.39 | 12.24 | 4.53 | 1.14 | 5.83 | 0.71 | 8.69 | 4.82 | 1.80 | 3.11 | 0.41 | 8.66 | 3.45 | 1.68 |
| SG-720 | 3.63 | 0.34 | 12.87 | 3.68 | 0.92 | 4.97 | 0.63 | 8.75 | 5.03 | 1.77 | 2.35 | 0.42 | 7.69 | 3.06 | 1.47 |
| Pr>F* | | | | | | | | | | | | | | | |
| $CO_2$ | 0.011 | 0.018 | 0.385 | 0.018 | 0.144 | 0.085 | 0.159 | 0.005 | 0.860 | 0.013 | 0.003 | 0.216 | 0.002 | 0.010 | 0.014 |
| Spp | 0.0001 | 0.007 | 0.264 | 0.006 | <0.0001 | 0.0001 | 0.040 | 0.343 | 0.003 | <0.0001 | <0.0001 | 0.124 | 0.001 | 0.140 | 0.892 |
| $CO_2$ x Spp | 0.937 | 0.298 | 0.190 | 0.262 | 0.598 | 0.781 | 0.567 | 0.004 | 0.454 | 0.029 | 0.011 | 0.115 | 0.030 | 0.931 | 0.302 |
| Content | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| SB-360 | 5.53 | 0.28 | 4.98 | 2.85 | 1.22 | 4.55 | 0.34 | 3.30 | 1.95 | 1.02 | 4.22 | 0.18 | 1.46 | 1.11 | 0.52 |
| SB-720 | 6.04 | 0.30 | 4.78 | 3.37 | 1.29 | 7.76 | 0.52 | 3.87 | 3.31 | 1.63 | 3.81 | 0.22 | 1.10 | 1.52 | 0.62 |
| SG-360 | 2.49 | 0.18 | 5.68 | 2.10 | 0.53 | 3.03 | 0.37 | 4.43 | 2.50 | 0.93 | 0.76 | 0.10 | 2.12 | 0.85 | 0.41 |
| SG-720 | 2.11 | 0.20 | 7.50 | 2.14 | 0.53 | 3.31 | 0.43 | 5.82 | 3.34 | 1.18 | 0.69 | 0.12 | 2.26 | 0.90 | 0.43 |
| Pr>F | | | | | | | | | | | | | | | |
| $CO_2$ | 0.776 | 0.150 | 0.255 | 0.042 | 0.674 | 0.001 | 0.028 | 0.001 | 0.011 | 0.001 | 0.560 | 0.108 | 0.366 | 0.15 | 0.158 |
| Spp | 0.005 | 0.033 | 0.116 | 0.001 | <0.0001 | 0.001 | 0.670 | 0.024 | 0.396 | 0.031 | <0.0001 | 0.010 | 0.0002 | 0.001 | 0.010 |
| $CO_2$ x Spp | 0.092 | 0.755 | 0.173 | 0.061 | 0.713 | 0.001 | 0.160 | 0.018 | 0.348 | 0.018 | 0.684 | 0.658 | 0.065 | 0.045 | 0.327 |

*Significance levels from the mixed models procedure of SAS.

Table 4

Copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) stover micronutrient concentrations (mg $kg^{-1}$) and contents (mg $m^{-2}$) for soybean (SB) and sorghum (SG) grown under ambient (360) and twice ambient (720) $CO_2$ conditions for three growing seasons (1992–1994)

| | 1992 | | | | 1993 | | | | 1994 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc. | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn |
| SB-360 | 7.40 | 79.01 | 76.64 | 14.72 | 8.51 | 31.01 | 89.73 | 17.91 | 4.96 | 96.26 | 30.05 | 10.90 |
| SB-720 | 6.48 | 57.93 | 65.91 | 14.28 | 5.93 | 36.87 | 88.34 | 18.51 | 4.52 | 96.25 | 32.72 | 11.82 |
| SG-360 | 17.58 | 114.15 | 179.92 | 24.01 | 15.18 | 61.46 | 138.01 | 21.43 | 4.52 | 96.21 | 63.96 | 24.67 |
| SG-720 | 17.93 | 107.02 | 128.97 | 19.32 | 11.10 | 46.82 | 116.92 | 21.26 | 4.52 | 96.23 | 46.85 | 24.74 |
| Pr>F* | | | | | | | | | | | | |
| $CO_2$ | 0.838 | 0.460 | 0.0003 | 0.043 | 0.112 | 0.715 | 0.127 | 0.565 | 0.373 | 0.999 | 0.007 | 0.743 |
| Spp | 0.0002 | 0.150 | <0.0001 | 0.054 | 0.016 | 0.220 | 0.004 | 0.083 | 0.421 | 0.997 | <0.0001 | <0.0001 |
| $CO_2$ x Spp | 0.645 | 0.707 | 0.004 | 0.073 | 0.691 | 0.412 | 0.167 | 0.326 | 0.372 | 0.998 | 0.002 | 0.781 |
| Content | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn |
| SB-360 | 2.91 | 31.35 | 30.40 | 5.85 | 2.52 | 8.99 | 25.96 | 5.18 | 1.45 | 28.03 | 8.72 | 3.17 |
| SB-720 | 3.18 | 27.96 | 32.74 | 7.11 | 3.07 | 18.96 | 45.48 | 9.54 | 1.97 | 42.11 | 14.34 | 5.18 |
| SG-360 | 8.15 | 52.92 | 83.48 | 11.11 | 7.76 | 32.85 | 71.36 | 11.08 | 1.11 | 23.37 | 15.78 | 6.08 |
| SG-720 | 10.47 | 61.66 | 74.84 | 11.20 | 7.34 | 31.23 | 77.79 | 14.17 | 1.33 | 28.31 | 13.82 | 7.26 |
| Pr>F | | | | | | | | | | | | |
| $CO_2$ | 0.200 | 0.750 | 0.300 | 0.128 | 0.933 | 0.554 | 0.027 | <0.0001 | 0.003 | 0.005 | 0.104 | 0.015 |
| Spp | 0.0004 | 0.014 | <0.0001 | 0.062 | 0.001 | 0.182 | 0.001 | 0.005 | 0.001 | 0.033 | 0.014 | 0.001 |
| $CO_2$ x Spp | 0.299 | 0.478 | 0.095 | 0.168 | 0.527 | 0.422 | 0.160 | 0.043 | 0.129 | 0.051 | 0.007 | 0.450 |

*Significance levels from the mixed models procedure of SAS.

sorghum; elevated $CO_2$ did lead to a smaller significant increase in soybean Zn content in 1993. However, in 1994, the interaction indicated that Fe and Mn stover contents were higher only for elevated $CO_2$-grown soybean.

## Roots

Root N, P, Ca, and Mg concentrations were lower in sorghum than soybean except for N in 1994 (Table 5). However, root K concentrations were significantly higher for sorghum compared to soybean in all years. Root N concentrations were lower under high $CO_2$ for soybean only in 1992. Significant main effects of $CO_2$ indicated that root N concentration was lower under elevated $CO_2$ in 1993 with a similar trend noted in 1994. Similarly, significant main effects of $CO_2$ for root P and Ca concentrations were noted in 1992. In 1994, elevated $CO_2$ significantly lowered root P, K, Ca, and Mg concentration in soybean only.

Root N, P, Ca, and Mg contents were lower in sorghum than soybean (Table 5). However, root K contents were significantly higher for sorghum compared to soybean in all years. There was a trend for elevated $CO_2$ to increase root N content, but this was only significant for soybean in 1993. Significant main effects of $CO_2$ indicated that root P, K, Ca, and Mg contents were higher under elevated $CO_2$ in 1992 with a similar trend noted in 1993 for P. In 1993, elevated $CO_2$ significantly increased root Ca and Mg content in soybean only. In this same year, growth under elevated $CO_2$ resulted in significantly higher root P and K contents in sorghum; a trend for a similar effect was noted for soybean in 1994 for K content.

The main effects of crop species on root micronutrient concentrations were significant primarily in 1992 and 1994 (Table 6). In general, differences in root micronutrient concentration between crops vary widely between years. Significant main effects of $CO_2$ indicated that root Cu (1992) and Zn (1994) concentrations were lower under elevated $CO_2$ conditions with a similar trend noted for Mn concentration in 1994. Significant $CO_2$ by crop species interactions indicated that elevated $CO_2$ lowered Zn (1992) and Mn (1994) concentrations in soybean; elevated $CO_2$ also led to a smaller significant decrease in Zn concentration for sorghum in 1992. In contrast, it was noted that sorghum root Fe concentration was increased by elevated $CO_2$ in 1994.

As noted for root micronutrient concentration, the main effects of crop species were significant (mainly in 1992 and 1994) and differences between crops for micronutrient content were variable across years (Table 6). Significant main effects of $CO_2$ indicated that root Cu (1994), Fe (1992), and Mn (1992 and1993) contents were higher under elevated $CO_2$. In 1994, Fe and Mn contents were increased by elevated $CO_2$ for the sorghum crop only. For Zn content in this same year, elevated $CO_2$ led to an increased content for the sorghum crop, but the opposite was true for the soybean crop.

Table 5

Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) root macronutrient concentrations (g $kg^{-1}$) and contents (g $m^{-2}$) for soybean (SB) and sorghum (SG) grown under ambient (360) and twice ambient (720) $CO_2$ conditions for three growing seasons (1992–1994)

| | 1992 | | | | | 1993 | | | | | 1994 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc. | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| SB-360 | 8.15 | 0.45 | 2.27 | 3.97 | 1.80 | 11.41 | 1.10 | 3.50 | 3.60 | 2.13 | 5.19 | 0.48 | 1.40 | 2.52 | 0.98 |
| SB-720 | 6.75 | 0.37 | 1.77 | 3.56 | 1.63 | 10.07 | 1.09 | 3.13 | 3.99 | 2.24 | 4.50 | 0.28 | 0.65 | 1.59 | 0.69 |
| SG-360 | 2.52 | 0.24 | 8.52 | 2.02 | 0.51 | 3.51 | 0.29 | 8.93 | 1.74 | 0.60 | 5.20 | 0.45 | 2.12 | 1.81 | 0.73 |
| SG-720 | 2.15 | 0.23 | 9.37 | 1.93 | 0.48 | 2.47 | 0.29 | 7.99 | 1.60 | 0.50 | 4.37 | 0.47 | 2.48 | 1.70 | 0.71 |
| Pr>F* | | | | | | | | | | | | | | | |
| $CO_2$ | 0.007 | 0.087 | 0.748 | 0.067 | 0.256 | 0.058 | 0.906 | 0.474 | 0.451 | 0.949 | 0.145 | 0.083 | 0.314 | 0.002 | 0.010 |
| Spp | <0.0001 | <0.0001 | 0.001 | 0.003 | <0.0001 | <0.0001 | <0.0001 | 0.035 | <0.0001 | <0.0001 | 0.905 | 0.166 | 0.0004 | 0.207 | 0.191 |
| $CO_2$ x Spp | 0.070 | 0.169 | 0.255 | 0.191 | 0.355 | 0.785 | 0.896 | 0.750 | 0.139 | 0.247 | 0.892 | 0.054 | 0.021 | 0.005 | 0.014 |
| Content | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| SB-360 | 1.64 | 0.09 | 0.46 | 0.80 | 0.36 | 1.79 | 0.17 | 0.55 | 0.56 | 0.33 | 1.01 | 0.09 | 0.28 | 0.49 | 0.19 |
| SB-720 | 1.93 | 0.11 | 0.50 | 1.02 | 0.47 | 2.27 | 0.25 | 0.71 | 0.92 | 0.51 | 1.26 | 0.08 | 0.18 | 0.47 | 0.20 |
| SG-360 | 0.33 | 0.03 | 1.11 | 0.26 | 0.06 | 0.79 | 0.07 | 2.05 | 0.40 | 0.14 | 0.64 | 0.05 | 0.26 | 0.22 | 0.09 |
| SG-720 | 0.39 | 0.04 | 1.67 | 0.35 | 0.09 | 0.66 | 0.08 | 2.14 | 0.43 | 0.14 | 0.81 | 0.08 | 0.45 | 0.32 | 0.13 |
| Pr>F | | | | | | | | | | | | | | | |
| $CO_2$ | 0.169 | 0.021 | 0.021 | 0.036 | 0.058 | 0.157 | 0.091 | 0.592 | 0.019 | 0.005 | 0.107 | 0.355 | 0.280 | 0.460 | 0.231 |
| Spp | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.009 | 0.007 | 0.005 | 0.053 | 0.017 | 0.084 | 0.073 | 0.018 | 0.002 | 0.003 |
| $CO_2$ x Spp | 0.332 | 0.786 | 0.042 | 0.248 | 0.170 | 0.040 | 0.187 | 0.866 | 0.037 | 0.005 | 0.717 | 0.038 | 0.008 | 0.143 | 0.275 |

*Significance levels from the mixed models procedure of SAS.

Table 6

Copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) root micronutrient concentrations (mg $kg^{-1}$) and contents (mg $m^{-2}$) for soybean (SB) and sorghum (SG) grown under ambient (360) and twice ambient (720) $CO_2$ conditions for three growing seasons (1992–1994).

| | 1992 | | | | 1993 | | | | 1994 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc. | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn |
| SB-360 | 14.37 | 675.27 | 57.14 | 110.78 | 26.25 | 1068.87 | 55.12 | 87.84 | 4.75 | 206.44 | 27.36 | 31.52 |
| SB-720 | 11.08 | 603.42 | 50.33 | 72.53 | 20.17 | 1014.35 | 75.11 | 61.25 | 4.52 | 154.00 | 16.77 | 16.89 |
| SG-360 | 8.28 | 485.71 | 77.60 | 35.4 | 59.80 | 607.10 | 72.66 | 40.12 | 7.10 | 507.49 | 52.75 | 60.52 |
| SG-720 | 5.79 | 454.36 | 72.89 | 25.42 | 18.68 | 721.56 | 81.11 | 41.20 | 7.10 | 666.66 | 54.56 | 55.98 |
| Pr>F* | | | | | | | | | | | | |
| $CO_2$ | 0.095 | 0.199 | 0.107 | <0.0001 | 0.207 | 0.917 | 0.262 | 0.370 | 0.346 | 0.161 | 0.032 | 0.040 |
| Spp | 0.006 | 0.112 | 0.0004 | <0.0001 | 0.379 | 0.212 | 0.347 | 0.036 | <0.0001 | 0.022 | 0.001 | <0.0001 |
| $CO_2$ x Spp | 0.802 | 0.579 | 0.742 | 0.0002 | 0.338 | 0.769 | 0.638 | 0.332 | 0.344 | 0.027 | 0.010 | 0.218 |
| Content | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn | Cu | Fe | Mn | Zn |
| SB-360 | 2.86 | 137.43 | 11.49 | 22.20 | 4.30 | 156.25 | 8.38 | 13.35 | 0.93 | 39.85 | 5.31 | 6.12 |
| SB-720 | 3.16 | 171.97 | 14.35 | 20.67 | 4.65 | 246.06 | 17.96 | 14.52 | 1.27 | 43.44 | 4.76 | 4.99 |
| SG-360 | 1.10 | 63.55 | 10.20 | 4.66 | 14.20 | 137.38 | 16.47 | 9.17 | 0.86 | 58.98 | 6.30 | 7.53 |
| SG-720 | 1.63 | 82.55 | 13.10 | 4.57 | 5.11 | 197.38 | 22.26 | 11.17 | 1.34 | 119.56 | 10.31 | 10.62 |
| Pr>F | | | | | | | | | | | | |
| $CO_2$ | 0.683 | 0.098 | 0.029 | 0.518 | 0.369 | 0.255 | 0.062 | 0.600 | 0.002 | 0.006 | 0.033 | 0.036 |
| Spp | 0.002 | 0.041 | 0.272 | <0.0001 | 0.035 | 0.596 | 0.114 | 0.255 | 0.973 | 0.005 | 0.027 | 0.015 |
| $CO_2$ x Spp | 0.503 | 0.567 | 0.983 | 0.564 | 0.337 | 0.814 | 0.592 | 0.887 | 0.247 | 0.008 | 0.014 | 0.003 |

*Significance levels from the mixed models procedure of SAS.

## DISCUSSION

In terms of differences between crop species, the concentrations and contents of primary (i.e., N, P, and K) and secondary nutrients (i.e., Ca and Mg) were generally higher for the soybean crop compared to the sorghum crop. This trend was true across the various soybean tissue types (grain, stover, and roots) for the macronutrients evaluated, except for K where measures were usually higher for the sorghum crop. In comparison, evaluation of micronutrient (i.e., Cu, Fe, Mn, and Zn) concentrations and contents were more variable than the macronutrient data. For grain tissue, both concentrations and contents of micronutrients were consistently higher for soybean across years compared to sorghum. For stover, the general trend was for sorghum measures to be higher except for in 1994 when Cu and Fe contents for soybean were higher. Evaluation of root tissue indicated a lot of variability across years, and no consistent pattern emerged for micronutrients differences between the two crop species.

Previous reports on this field study showed that elevated atmospheric $CO_2$ led to increases in dry matter production for these crops (Prior et al., 1997; 2003; 2004). Based on reviews of the literature, nutrient concentrations are often found to be lower under elevated $CO_2$ due to a dilution effect caused by increases in biomass (Rogers, Runion, and Krupa 1994; Rogers et al., 1999). In this study, nutrient concentrations tended to be higher for ambient grown $CO_2$ crops compared to those raised under elevated $CO_2$ conditions. This overall effect of elevated $CO_2$ was more notable for macronutrient vs. micronutrient concentrations and this main effect of $CO_2$ was reflected more in stover and root tissue compared to grain tissue. In general, Cu and Fe tended to be more highly variable compared to Mn and Zn when viewed across years and/or tissue types. Further, in the instances of significant $CO_2$ by crop species interactions, the same general pattern as seen for the main effect of $CO_2$ was observed (i.e., ambient being higher than elevated $CO_2$). In most cases, the lowering of nutrient concentrations attributable to the elevated $CO_2$ treatment was observed in the soybean crop. In instances where both crops were significantly affected by elevated $CO_2$, the differences in nutrient concentration were often greater for soybean compared to sorghum.

Nutrient contents tended to be higher under elevated $CO_2$ verses ambient $CO_2$ conditions which is in general agreement with reports of higher nutrient content under $CO_2$ enrichment. Increased nutrient content can be attributed to greater biomass production occurring under high $CO_2$ (Rogers, Runion, and Krupa 1994; Rogers et al., 1999). This main effect of $CO_2$ was always true for grain macronutrients with a few exceptions noted for micronutrients. Similar response patterns were noted for stover and root macronutrient contents, however, micronutrient contents were more variable for these tissue types. There were numerous cases of significant $CO_2$ by crop species interactions, especially for grain macronutrients. Overall, fewer significant interactions were noted for micronutrient contents compared to macronutrient contents for the different tissue types examined. In most cases, elevated $CO_2$ led to increased nutrient contents for only the soybean crop. The main exception to this trend occurred for K where sorghum contents were greater than those observed in soybean (e.g, 1993 stover and 1994 root). Even when both crops were significantly affected by elevated $CO_2$, the increase in nutrient content was often greater for the soybean crop. These results were not surprising given that previous reports on this field research had shown that soybean often showed a greater biomass response to elevated $CO_2$ than the sorghum crop (Prior et al., 1997; 2003; 2004).

To date, the majority of reports in the literature regarding $CO_2$ effects on plant nutrient characteristics have been conducted under non-field conditions. Results reported here are based on a field study conducted over three years. In general, results indicate that changes in atmospheric $CO_2$ conditions will have a greater impact on soybean cropping systems. Further, our findings suggest that forecasting elevated atmospheric $CO_2$ impact on crop nutrient dynamics will be more straightforward for macronutrients, which were much less variable compared to micronutrients. This appears to be particularly true for cropping system outputs reflected by consistent $CO_2$-induced increases in grain nutrient content. Predictions on how changing atmospheric $CO_2$ level will increase the amount of crop nutrient inputs (i.e., stover and root contents) to the soil are less robust due to variability observed in these tissue types across years. Again, this is particularly true for micronutrients. It should be noted that a similar evaluation of nutrient characteristics of a cotton crop grown in the field under $CO_2$ enrichment also found variable results across two growing seasons (Prior et al., 1998). Therefore, noted deviations from the general trends in the literature may be a result of the more realistic growth conditions in these field studies; in particular, the fact that crops were grown without root restriction may help explain our findings. Further, it is likely that differences among years could be attributed to seasonal fluctuations in environmental conditions occurring in the field. Lastly, it is important to note that this study was based on analysis of senesced plant material while others have generally used green tissue.

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