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ELEVATED ATMOSPHERIC CO_2 IN AGROECOSYSTEMS: SOIL PHYSICAL PROPERTIES

Stephen A. Prior, G. Brett Runion, H. Allen Torbert, and Hugo H. Rogers

Increased crop biomass production caused by elevated atmospheric CO_2 concentration suggests more carbon input to the soil, which could alter soil physical properties. Soil samples were collected from the surface layer (0–6 cm) after 5 years of soybean [*Glycine max* (L.) Merr.] or sorghum [*Sorghum bicolor* (L.) Moench.] production under two CO_2 levels (360 μLL^{-1} and 720 μLL^{-1}) on a Blanton loamy sand (loamy siliceous, thermic, Grossarenic Paleudults) under no-till management using open top field chambers in Auburn, Alabama. Soil carbon content, bulk density, saturated hydraulic conductivity, and water stable aggregates were measured. Soil carbon content was increased by elevated CO_2. Significant cropping system by CO_2 interactions were noted for soil bulk density and saturated hydraulic conductivity; aggregate stability exhibited a similar trend. In the soybean system, soil bulk density decreased whereas saturated hydraulic conductivity and aggregate stability increased as a result of elevated CO_2; however, CO_2 had little affect on soil properties in the sorghum system. Results indicate that greater nonyield biomass inputs could increase soil carbon content and improve soil physical properties, especially in soybean production systems. (Soil Science 2004; 169:434–439)

Key words: Carbon dioxide, soybean, sorghum, cropping systems, soil properties, C storage.

POPULATION increases, industrial expansion, and land use changes are significant factors that have contributed to the unprecedented rise in global atmospheric CO_2 concentration (Houghton et al., 2001). Because this trend is expected to continue, leading to further changes in the global environment (IPCC, 1996; Giorgi et al., 1998), questions concerning the potential impact on highly managed agricultural systems and soil resources have arisen (Polley, 2002; Soil and Water Conservation Society, 2003). Aboveground experimental work conducted over the last decade has resulted in several responses that could have important ramifications for crop production systems. Specifically, high CO_2 often increases water use efficiency, net photosynthesis, and biomass production and yield, and also alters plant tissue composition (Amthor, 1995; Rogers and Dahlman, 1993; Rogers et al., 1999; Kimball et al., 2002). Less research has been conducted examining the potential effects of CO_2 on root growth and other belowground processes under field conditions. Reviews have noted that a large proportion of the increase in biomass under CO_2-enriched conditions is found belowground (Rogers et al., 1994; 1996).

Shifts in the quantity and quality of crop residue can affect decomposition processes, which can then impact nutrient and carbon turnover as well as soil physiochemical properties. Enhanced aboveground crop growth under elevated CO_2, leading to more soil surface residue and greater percent ground cover (Prior et al., 1997) coupled with positive shifts in crop root systems (Prior et al., 2003), may have the potential to alter soil structural characteristics. Reported decreases in tissue N concentration in plants grown under

USDA-Agricultural Research Service, National Soil Dynamics Laboratory, 411 South Donahue Drive, Auburn, AL 36832. Dr. Prior is corresponding author. E-mail: sprior@acesag.auburn.edu

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elevated CO_2 increases the tissue C:N ratio (Cotrufo et al., 1998; Rogers et al., 1999; Kimball et al., 2002), an important factor influencing rates of decomposition (Parr and Papendick, 1978). The fate of residue derived from plants grown under elevated CO_2 has not been fully resolved. It has been suggested that a higher C:N ratio could slow residue decomposition, leading to increased soil C storage (Bazzaz, 1990), but slower residue decomposition resulting from elevated CO_2 is not well supported by the literature on litter quality (Hom, 2002). However, a recent review reported that even if decomposition rates of plant residue produced under CO_2 enrichment are not changed, the decomposition products of this residue may alter soil N dynamics (Torbert et al., 2000). This review suggested further that the biodegradability of crop residues and soil C storage may not only be affected by the environment, it may also be crop species-dependent. Such considerations may become more important when adapting future residue management scenarios to help mitigate the effects of global CO_2 rise by sequestering C in agricultural soils.

Agroecosystems are very time-dynamic, with choices of crop species and tillage operations being made on at least an annual basis. Cropping history and the soil tillage practice utilized will have a major impact on the amount of organic C stored in soil (Potter et al., 1997, 1998; Reicosky et al., 1997; Torbert et al., 1998). The interaction between elevated atmospheric CO_2 and crop production management can only be analyzed through long-term studies in the field that explore different management scenarios. Understanding these interactions will be essential to assessing the potential impact of elevated CO_2 on soil physical properties in agroecosystems. In the current study, soybean (a C_3 crop) and sorghum (a C_4 crop) were grown in a large outdoor soil bin, without root restriction, under two different atmospheric CO_2 levels (ambient and twice ambient CO_2 levels) for five growing seasons using no-tillage management. These two crops were selected to provide widely produced legume and nonlegume test crops (FAO, 1996). Our study design allowed for C_3 legume and C_4 nonlegume crops to be grown concurrently under the same experimental conditions to determine the effects of differing cropping systems on soil physical properties under ambient and elevated atmospheric CO_2 concentrations.

MATERIALS AND METHODS

Soybean (Stonewall) and grain sorghum (Savanna 5) were selected to provide the legume and nonlegume test crops that are widely produced in agroecosystems (FAO, 1996). The plants were grown from seed to maturity in open top field chambers (Rogers et al., 1983) at two atmospheric CO_2 concentrations (360 and 720 μLL^{-1}). The experiment was conducted on an outdoor soil bin (Batchelor, 1984) located at the USDA-ARS National Soil Dynamics Laboratory, Auburn, Alabama (32.6° N, 85.5° W). The soil was a Blanton loamy sand (loamy, siliceous, thermic Grossarenic Paleudult) that had been fallow for more than 25 years prior to the study. This fallow period was followed by five seasons of soybean and sorghum grown under no-tillage conditions. Here we report results of 5 years of treatment history on soil physical properties.

The open top field chambers were constructed of a structural aluminum frame (3 m in diameter by 2.4 m in height) covered with a PVC film panel (0.2 mm thickness), similar to those described in detail by Rogers et al. (1983). Carbon dioxide was supplied by a 12.7-Mg liquid CO_2 receiver through a high volume dispensing manifold, and the atmospheric CO_2 concentration was elevated by continuous injection of CO_2 into plenum boxes. Air was introduced into each chamber through the bottom half of each chamber cover, which was double-walled; the inside wall was perforated with 2.5-cm-diameter holes to serve as ducts to distribute air uniformly into the chamber. Three chamber volumes were exchanged every minute. Carbon dioxide concentrations were monitored continuously (24 h d^{-1}) using a time-shared manifold with samples drawn through solenoids to an infrared CO_2 analyzer (Model 6252, LI-COR, Inc., Lincoln, NE). Values were recorded continuously every 15 to 30 min for each chamber, depending on whether an additional CO_2 study was on line.

Soybean seeds were inoculated with commercially available *Rhizobium japonicum* (Lipha Tech, Inc., Milwaukee, WI), and the seeds were then sown in 6-m rows oriented across the width of the soil bin. The distance between rows was 0.76 m. Plants were thinned for uniformity to a final density of 30 and 26 plants m^{-2} for soybean and sorghum, respectively. To ensure adequate plant establishment, fertilizer N in the form of ammonium nitrate was broadcast at a rate of 34 kg N ha^{-1} shortly after planting. In the grain sorghum, an additional 67 kg N ha^{-1} was applied 30 days after planting. All plots received ambient rainfall and were irrigated only when necessary to prevent drought-induced mortality; a drip irrigation system was used to distribute water uniformly throughout the bin. The average annual rainfall amounts were 480, 421, 867, 588, and 555 mm for each respective growing season. Weed control was done by hand and/or by use of glyphosate (N–[phosphonomethyl] glycine).

At harvest time, grain sorghum heads and soybean pods were removed from plants and processed through a plot combine. To approximate a machine harvest, plant stalks within each chamber were cut into 15-cm pieces using hedge clippers. Aboveground nonyield residues (stalks, soybean pod hulls, and sorghum chaff), including 10% (by weight) of the grain yield, were returned back to the study plots to simulate normal no-tillage farm operations (Prior et al., 1997, 2003). After the harvests, the chambers were removed, but their locations remained fixed and were delineated by permanent 3-m aluminum rings. Bird netting (1.6-cm by 1.9-cm openings; Dalen Products, Inc., Knoxville, TN) was placed over the entire soil bin to prevent movement of aboveground residue into or out of plots during the overwintering period. All chambers were reinstalled in the spring of each year after planting.

In 1997, soil cores (5.3 × 6 cm) were collected after the winter fallow to determine saturated hydraulic conductivity according to the method of Klute and Dirksen (1986). Five soil cores were collected randomly from each chamber plot. After hydraulic conductivity was determined, assessment of bulk density was made on these same core subsamples (Blake and Hartge 1986). For wet aggregate stability determinations (Kemper and Rosenau, 1986), composite shovel samples (0–6-cm depth) were collected from each chamber plot, with a total of 10 subsamples taken from each chamber plot. Soil C and N were also assessed with samples sieved (2-mm mesh) to remove residue fragments, dried (55 °C), and ground with a roller grinder (Kelley, 1994) to pass a 1 mm mesh. A total of four subsamples per chamber plot were analyzed for N and C concentrations (Fison NA1500 CN Analyzer; Fison Instruments Inc., Beverly, MA). These N and C concentration numbers and bulk density values were used to calculate total N and C content.

The experiment was conducted using a split-plot design with three replicate blocks. Whole-plot treatments (crop system) were assigned randomly to half of each block. Subplot treatments (CO_2 levels) were assigned randomly to two chambers (3 m diameter) within each whole plot. Statistical analyses of data were performed using the Mixed procedure of the Statistical Analysis System (Littell et al., 1996). A significance level of $P < 0.10$ was established *a priori*.

RESULTS

Results indicated that increased atmospheric CO_2 had significant effects on soil physical properties after 5 years of cropping but varied for the two different cropping systems. For soil bulk density, a significant cropping system by CO_2 interaction was noted ($P = 0.024$; Fig. 1). In this case, no differences in soil bulk density were caused by elevated CO_2 in the sorghum system. However, in the soybean cropping system, soil bulk density was significantly lower (~5%) under CO_2-enriched conditions.

A significant cropping system by CO_2 interaction was also observed for saturated hydraulic conductivity ($P = 0.018$; Fig. 2). Similar to soil bulk density, saturated hydraulic conductivity was unaffected by CO_2 concentration in the sorghum cropping system. In the soybean cropping system, elevated CO_2 increased (~42%) saturated hydraulic conductivity significantly. For water stable aggregates, significant main effects of cropping system ($P = 0.007$) and CO_2 ($P = 0.074$) were noted (Fig. 3). Compared with the soybean cropping system, aggregate stability was greater in the sorghum cropping system. The significant main effect of CO_2 indicated that elevated CO_2 increased aggregate stability. It is noteworthy that a trend for a cropping system by CO_2 interaction

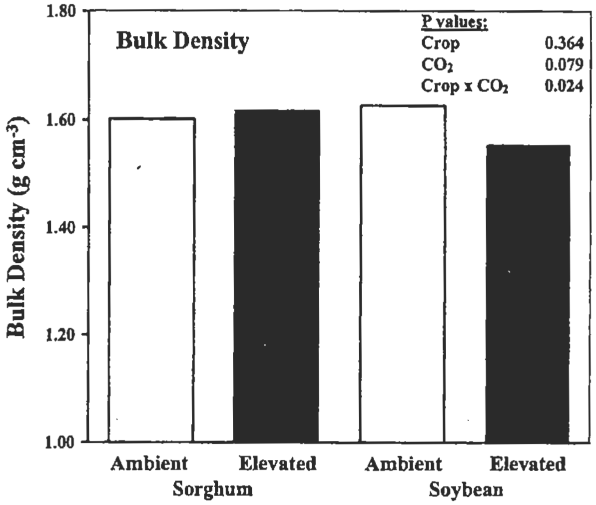

Fig. 1. Effect of atmospheric CO_2 concentration (ambient or elevated) on soil bulk density in sorghum and soybean cropping systems. Probability values (Pr > F) for main effect and interaction terms are shown. Bars represent means ($n = 3$).

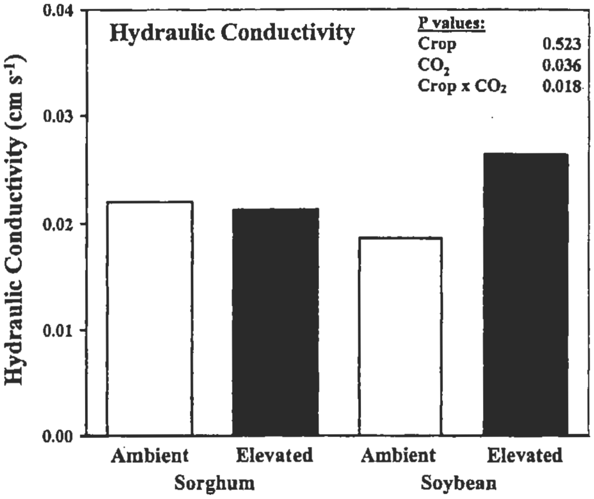

Fig. 2. Effect of atmospheric CO_2 concentration (ambient or elevated) on saturated soil hydraulic conductivity in sorghum and soybean cropping systems. Probability values (Pr > F) for main effect and interaction terms are shown. Bars represent means ($n = 3$).

($P = 0.159$) was observed, suggesting more of a CO_2-induced increase in aggregate stability for the soybean cropping system.

Total soil C content was increased by 16 and 29% under CO_2-enriched conditions in the sorghum and soybean cropping systems, respectively ($P = 0.045$; Fig. 4). We did not find a significant system by CO_2 interaction for total soil C content ($P = 0.397$). The main effect of a system was also not significant ($P = 0.162$).

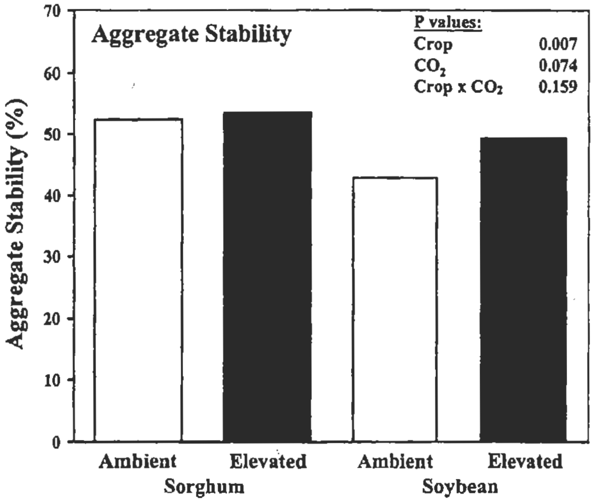

Fig. 3. Effect of atmospheric CO_2 concentration (ambient or elevated) on soil aggregate stability in sorghum and soybean cropping systems. Probability values (Pr > F) for main effect and interaction terms are shown. Bars represent means ($n = 3$).

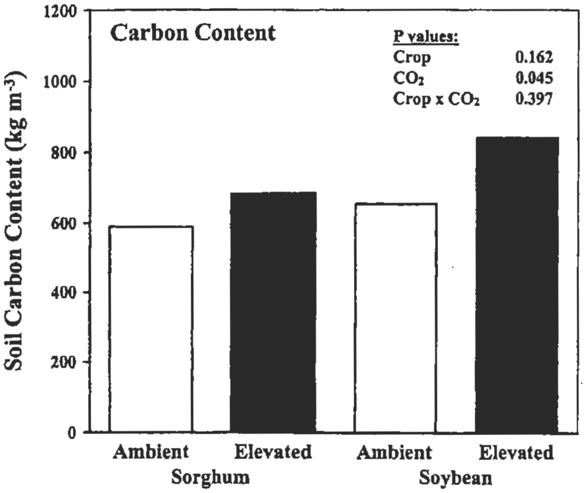

Fig. 4. Effect of atmospheric CO_2 concentration (ambient or elevated) on soil carbon content in sorghum and soybean cropping systems. Probability values (Pr > F) for main effect and interaction terms are shown. Bars represent means ($n = 3$).

DISCUSSION

In conservation tillage and no-tillage systems, a higher accumulation of nonyield biomass can be expected along with improvements in soil properties and increased soil carbon. Previous reports from this study showed that elevated CO_2 did increase nonyield biomass returned to the soil surface and percent ground cover (Prior et al., 1997). Work also showed that CO_2 enrichment had more effect on increasing soybean residue compared with sorghum, but no significant effect of CO_2 level on residue decomposition using litter bags was found (Prior et al., 2004). Mass loss patterns indicated a crop species effect which varied by tissue type. Soybean leaf decomposition proceeded more rapidly than sorghum (due to lower C:N ratio); however, the opposite effect occurred for stem and root residues. Even though the CO_2 level did not affect residue recovery, greater residue production under high CO_2 resulted in more residue remaining after the winter fallow period. The development of an extensive residue mat should not only promote more favorable soil surface characteristics but should also improve subsurface soil physical properties, as was shown in this study (Figs. 1–3). Furthermore, soil carbon content was increased by CO_2 enrichment in this no-tillage system (Fig. 4).

Improved soil physical properties were also likely related to CO_2-induced shifts in rooting. Stabilization of the soil matrix from the more prolific root systems under elevated CO_2 can be inferred from increases in vertical root-pulling resistance (Prior et al., 1995, 2003). Fine root density patterns (both length and dry weight) were also assessed in the current study, and the extent of CO_2-induced changes were found to be crop dependent: elevated CO_2 had a much greater positive effect in the soybean compared with sorghum cropping system (Prior et al., 2003) as has been generally observed in C_3 vs C_4 comparisons. Positive shifts in root systems growth may have altered soil structural characteristics (e.g., because of increased number and extent of root channels). Such changes, in conjunction with root turnover, root exudation, and other biological activity (increased populations of microbes and soil fauna and fungi), may have influenced soil aggregate formation positively. Further, it has been shown that soil aggregate stability can be correlated tightly with the concentration of glomalin—a glycoprotein produced by arbuscular mycorrhizal fungi—in the soil (Rillig et al., 1999). Although not measured directly, it is quite possible that increased glomalin concentration played a role in the CO_2-induced increase in aggregate stability noted; percent mycorrhizal colonization of roots was similar (34.5 and 32.4% for ambient and elevated CO_2, respectively; data not shown), whereas elevated CO_2 increased root length significantly (Prior et al., 2003), suggesting an increase in total mycorrhizae in this study.

Our evaluation of soil physical characteristics indicated that soil structure was altered by elevated CO_2, particularly in the soybean system. In this case, the soil had lower bulk density values, more water stable aggregates, and exhibited positive shifts in saturated hydraulic conductivity, suggesting that soil porosity had been increased under elevated CO_2. Such changes may be caused, in part, by a greater positive affect of elevated CO_2 on soybean fine root density patterns in combination with soybean residue quality (lower C:N ratio) (Prior et al., 2003). Detailed examination of residue input (quality and quantity) in relation to soil C and N dynamics indicates that N availability exerts a strong influence on decomposition processes (Torbert et al., 2000), which may alter soil physicochemical characteristics, leading to an improvement in overall soil quality.

CONCLUSIONS

Findings suggest that soil physical properties in agroecosystems may be altered in a future CO_2-enriched environment. These results indicate potential for improvements in soil carbon storage, water infiltration and soil water retention, and reduced erosion. However, such CO_2-induced benefits may favor legume-based systems such as soybean. Crop selection may become more important in designing future management strategies to take full advantage of the rise in atmospheric CO_2 concentration.

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