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Elevated atmospheric CO_2 effects on N fertilization in grain sorghum and soybean

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Abstract

Increasing atmospheric CO_2 concentration has led to concerns about global changes to the environment. One area of global change that has not been fully addressed is the effect of elevated atmospheric CO_2 on agriculture production inputs. Elevated CO_2 concentration alterations of plant growth and C:N ratios may modify C and N cycling in soil and N fertility. This study was conducted to examine the effects of legume, soybean (*Glycine max* (L.) Merr.), and non-legume, grain sorghum (*Sorghum bicolor* (L.) Moench.) carbon dioxide-enriched agro-ecosystems on N soil fertility in a Blanton loamy sand (loamy siliceous, thermic, Grossarenic Paleudults). The study was a split-plot design replicated three times with crop species (soybean and grain sorghum) as the main plots and CO_2 concentration (ambient and twice ambient) as subplots using open top field chambers. Fertilizer application was made with ^{15}N-depleted NH_4NO_3 to act as a fertilizer tracer. Elevated CO_2 increased total biomass production in all 3 years of both grain sorghum (average 30%) and soybean (average 40%). With soybean, while no impact on the plant C:N ratio was observed, the total N content was greatly increased (average 29%) due to increased atmospheric N_2 fixation with elevated CO_2 concentration. With grain sorghum, the total N uptake was not affected, but the C:N ratio was markedly increased (average 31%) by elevated CO_2. No impact of elevated CO_2 level was observed for fertilizer N in grain sorghum. The results from this study indicated that while elevated CO_2 may enhance crop production and change N status in plant tissue, changes to soil N fertilizer application practices may not be needed.

Keywords: Carbon dioxide; Fertilizer nitrogen dynamics; ^{15}N; *Glycine max*; *Sorghum bicolor*

1. Introduction

There are continued concerns regarding the increasing level of CO_2 in the atmosphere (IPCC, 1996; Giorgi et al., 1998) and its potential impact on agriculture production and soil resources (Polley, 2002; Soil and Water Conservation Society, 2003). The positive response of crops to elevated CO_2 is well documented, with experimental work showing that high CO_2 often increases water use efficiency, net photosynthesis, biomass production, and yield (Rogers and Dahlman, 1993; Rogers et al., 1999; Kimball et al., 2002). These direct effects could have important ramifications for agricultural production systems. Less research has been done to examine the effects of elevated CO_2 under field conditions, where nutrient availability will be a key factor in crop response. The impact on N dynamics is especially important, since it has been commonly

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reported that N concentration is reduced in plants grown under elevated CO_2 (Cotrufo et al., 1998; Rogers et al., 1999; Kimball et al., 2002).

The sustainability of any crop production system depends on maintaining adequate soil plant nutrient levels. Nitrogen is the nutrient that is most often limiting in agro-ecosystems, resulting in fertilizer N being the most common and often the most expensive fertilizer addition for the production of non-legume crops. In the USA, approximately 11.1 million metric t of N were applied to cropland in 1998 (AREI, 2000). In addition, the symbiotic fixation of atmospheric N_2 involving *Rhizobium japonicum* with legume crops is significant because this enhances available N in many cropping systems.

Most N transformations in soil are regulated by microbial activity and organic matter content (Hart et al., 1993). For example, inorganic N levels are regulated by the balance between mineralization and immobilization of N in organic matter (Jansson and Persson, 1982; Van Miegroet et al., 1992). A potential effect of plant growth at elevated CO_2 may be an increased level of organic C in soil impacting N dynamics, including regulation of biological activity. Soil N dynamics may also be affected by CO_2-induced alterations in soil and plant residue C:N ratios. For example, changes in the composition of litter in a CO_2-rich environment may reduce decomposition rates and limit nutrient cycling in soil (Cotrufo et al., 1994; Coûteaux et al., 1991). Recent work on plant decomposition indicated that even if decomposition rates of plant residue produced under CO_2 enrichment are not changed, the decomposition products of this residue may have a considerable impact on soil N dynamics (Torbert et al., 1995).

Research conducted to examine the effect of elevated CO_2 enrichment on plant productivity under varying resource limitations has indicated that while the absolute magnitude of plant growth is greatest under conditions of adequate resources, the relative response to elevated CO_2 is greatest under environmental stress and resource limitations (Rogers et al., 1999). Less effort has been spent on examining the impact on soil fertility practices and the fate of N fertilizer in cropping systems. Nitrogen and P are not only the two elements (along with K) that are most commonly added in large amounts as fertilizers, but they are also the two elements that will most likely be impacted by elevated CO_2 conditions because they are needed in relatively large amounts in the photo-reductive C cycle and the photo-oxidative cycle in plant growth (Rogers et al., 1999). In an examination of the potential impacts of the greenhouse effect on agriculture, Rosenzweig and Hillel (1998) indicated that if yields were increased by a third (as indicated in reviews by Kimball (1983) and Cure and Adcock (1986)), then we should expect an increase in fertilizer additions.

The impact of elevated atmospheric CO_2 on N fertilizer utilization is not only important because of its potential impact on crop productivity (and therefore the economic stability of agriculture), but also because soil fertility and nutrient additions (especially N and P) are inextricably linked to environmental quality (Sims, 1999). Additionally, N fertilizer utilization is a major component in the energy input and CO_2 balance of agriculture production (Schlesinger, 1999). Understanding the potential changes in the plant–soil interactions with N in crop production under elevated CO_2 will be critical to the management of N fertilizer for both profitable and environmentally sound agricultural systems in the future.

2. Materials and methods

This study was conducted in an outdoor soil bin at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL (32.6°N, 85.5°W). The bin was 2 m deep, 7 m wide, and 76 m long and was uniformly filled with surface soil of a Blanton loamy sand (loamy, siliceous, thermic Grossarenic Paleudults). The soil bin had been continuously bare fallow for over 25 years (Batchelor, 1984). The bottom of the bin (2 m depth) was covered with sand and gravel and was tile drained. Initial levels of P (8 kg ha^{-1}) and K (14 kg ha^{-1}) were in the ''very low'' range. Cation-exchange capacity averaged 2.45 $cmol_c$ kg^{-1} and soil pH averaged 4.7. The initial level of organic matter averaged 5.0 g kg^{-1} and total N was 0.06 g kg^{-1}. A more detailed description of the soil status prior to initiation of the study, fertilizer and lime amendments during the study, and subsequent soil analysis results have been reported previously (Reeves et al., 1994).

The study was a split-plot design replicated three times with main plots of two crop species, and two

CO_2-exposure regimes as subplots. Soybean 'Stonewall', and grain sorghum 'Savannah 5', were chosen as test crops to provide legume and non-legume species, respectively, that are widely produced in agro-ecosystems. The CO_2 exposure regimes were open top field chambers (total of 12) at ambient and twice ambient atmospheric CO_2 concentrations. 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*.

The open top field chambers, 3 m in diameter and 2.4 m high, are described in detail by Rogers et al. (1983b). Carbon dioxide concentrations were continuously monitored using a time-share manifold with samples drawn through solenoids to an infrared CO_2 analyzer[1] (LI-COR 6252, LI-COR Inc., Lincoln, NE). The atmospheric CO_2 concentration in the twice ambient chambers were continuously adjusted by injection of CO_2 into plenum boxes and air dispensed into each chamber through the bottom half of each chamber cover. The bottom half of the chamber cover was double-walled with the inside wall perforated with 2.5 cm diameter holes to serve as ducts to distribute air uniformly into the chamber. The mean seasonal daytime CO_2 concentrations were 357.4 ± 0.1 (S.E.) and 705.0 ± 0.3 $\mu l\, l^{-1}$ in 1992, 364.0 ± 0.2 and 731.7 ± 0.4 $\mu l\, l^{-1}$ in 1993 and 359.0 ± 0.1 and 706.9 ± 0.4 $\mu l\, l^{-1}$ in 1994, for ambient and enriched plots, respectively.

Soybean and grain sorghum seeds were sown in 6 m rows oriented across the width of the soil bin on 2 June, 5 May, and 6 May in 1992, 1993, and 1994, respectively. In 1994, sorghum plots were replanted in mid June because the first crop failed owing to root rot caused by moist cool soil. Soybean seeds were inoculated with commercial *Rhizobium* (Lipha Tech Inc., Milwaukee, WI) prior to planting. Plants were thinned for uniformity to a final density of 30 plants m^{-2} for soybean and 26 plants m^{-2} for sorghum.

All plots received ambient rainfall and were irrigated only when necessary to prevent drought-induced mortality. A drip irrigation system was used to uniformly distribute water throughout the bin. Total amounts of water received (rainfall + irrigation) were 623, 724, and 1001 mm for each respective growing season. Weeds were controlled by hand. In the off-season, weed control was both by hand and by use of glyphosate (*N*-(phosphonomethyl) glycine). For three seasons, plants were grown as described above and managed using no-till practices.

To ensure adequate plant establishment, fertilizer N was broadcast applied at a rate of 34 kg N ha^{-1} to both the grain sorghum and the soybean shortly after planting (4 June 1992, 6 May 1993, and 9 May 1994). In the grain sorghum, an additional 67 kg N ha^{-1} was applied 30 days after planting (3 July 1992, 7 June 1993, and 10 June 1994). Fertilizer application was made as NH_4NO_3, with one-half of the chamber plot area receiving an application of ^{15}N-depleted NH_4NO_3 containing 0.01 at.% ^{15}N and the other half receiving non-labeled NH_4NO_3 (0.3663 at.% ^{15}N). Application of the ^{15}N-depleted fertilizer was alternated to the other half of the chamber plot area in each subsequent year of study.

Plant samples (including roots), were collected at physiological maturity in all years for biomass and nutrient analyses from the chamber area which received application of the ^{15}N-depleted fertilizer that year. At harvest, 12 plants in 1992 and 16 plants in 1993 and 1994 were collected per chamber. Dry weights of organ parts were determined after over drying to constant weight at 55 °C. In addition, estimates of root system biomass were calculated based on retrieval from soil cores (Prior and Rogers, 1992).

Each year, a final harvest was conducted. Grain sorghum heads and soybean pods were removed from the plants and processed through a plot combine. Plant stalks were cut into approximately 15 cm lengths using hedge clippers and uniformly spread over the plots. Soybean pod hulls and grain sorghum chaff were also added back to the plots. To simulate seed loss during combining, 10 wt.% of the seed yield was returned to the plots. Following the final harvest, chambers were removed but their locations remained fixed and delineated by a permanent 3 m aluminum ring. Bird netting (1.6 cm × 1.9 cm opening; Dalen Products Inc., Knoxville, TN) was placed over the entire soil bin surface to prevent movement of above-ground residue into or out of the plots.

Plant samples were oven dried at 55 °C (until weight loss was complete) and ground in a Wiley mill to pass a 0.44 mm screen. Six soil cores (2.4 cm

[1] Trade names and products are mentioned solely for information. No endorsement by the USDA is implied.

diameter) were collected from each chamber at harvest each year to a depth of 105 cm and bulked by depth increments of 0–5, 5–10, 10–15, 15–30, 30–45, 45–60, 60–75, 75–90, and 90–105 cm. Intact soil cores were collected for bulk density determination for the same depth increments. Subsamples of the soils were dried (55 °C) and ground to pass a 0.15 mm sieve. Total C contents of plant and soil samples were determined using a Fison NA1500 CN analyzer (Fison Instruments Inc., Beverly, MA). Total N content of plant and soil samples was determined using a permanganate-reduced iron modification of a semimicro-Kjeldahl method (Bremner and Mulvaney, 1982). Distillates of plant and soil were concentrated for isotope-ratio analyses, which were performed as described by Mulvaney et al. (1990), using an automated mass spectrometer (Nuclide Model 3-60-RMS; Measurement and Analysis Systems, Bellefonte, PA). Fertilizer N recovery in grain sorghum and biological N_2 fixation of soybean were determined through isotope dilution methods (Hauck and Bremner, 1976), with grain sorghum used as the non-N_2-fixing reference plant. The term "*fertilizer-N*" is used to denote N added to the plant/soil system through fertilizer N application. The term "*fixed-N*" is used to denote plant N derived from biological N_2 fixation. The term "*native soil N*" is used to denote N from sources other than fertilizer N applied. Determination of whole plant and residue (root biomass and aboveground biomass−seed) total N uptake and fertilizer N content was made by summing N in individual plant parts. Nutrient utilization efficiency (unit of biomass produced per unit of N uptake) and fertilizer N efficiency (plant fertilizer N content per fertilizer N applied) were calculated. Soil fertilizer N content was obtained by summing fertilizer N content at each sampling depth.

3. Results and discussion

Elevated CO_2 has generally been shown to increase crop growth. Plant species with both C_3 and C_4 photosynthetic pathways exhibit growth stimulation due to lowered conductance and increased water use efficiency (Rogers et al., 1983a; Prior et al., 1991), but because of differences in CO_2 utilization during photosynthesis, plants with a C_3 photosynthetic pathway often exhibit greater growth response compared with plants with C_4 pathway (Bowes, 1993; Rogers et al., 1997). In this study, both the C_3 (soybean) and the C_4 (grain sorghum) crop species increased growth in response to elevated atmospheric CO_2 in all years of the study (Table 1). As noted in other studies (Kimball et al., 2002), the C_3 exhibited greater growth response compared to the C_4 crop, with an increase in total biomass production (averaged over all 3 years) of 30% for grain sorghum compared to 40% for soybean. A more detailed description of the elevated CO_2 results on biomass allocation in plant organs and root components has been reported previously (Prior et al., 2003). This study examined the impact of this growth response from elevated atmospheric CO_2 on soil N fertility.

The positive growth response to increased atmospheric CO_2 resulted in changes in plant N concentration and C:N ratio (Table 1), but the response was different between the two plant species. With grain sorghum in 1994, a significant reduction in N concentration was observed under the elevated CO_2 treatment compared to the ambient CO_2 treatment. In 1992 and 1993, while means were consistently lower for the elevated CO_2 treatment, no significant difference was observed in N concentration. This is consistent with many studies which have found that elevated CO_2 results in reduced N concentration in plant tissue (Cotrufo et al., 1998; Prior et al., 1998). However, no significant difference (or trend) was observed for total N uptake in the grain sorghum plants (Table 2). While CO_2 treatment did not affect plant C concentration (Table 1), a significant increase in total plant C (plant biomass) was observed. The result was a significant increase in the C:N ratio of the grain sorghum plant tissue (Table 1). This is also consistent with many published reports for plants grown under elevated CO_2 (Rogers et al., 1999; Hom, 2002).

Nitrogen utilization efficiency (NUEF) is a measure of the plant biomass production per unit N in the plant. With grain sorghum, elevated CO_2 significantly increased biomass production but had no effect on the amount of plant N uptake (Table 2). A significant increase was seen for the NUEF for grain sorghum grown under elevated CO_2 (Table 2). The increase in NUEF was relatively large, 21–33%, during the 3 years of study (Table 2). These results agree with those reported elsewhere (Fangmeier et al., 1997;

Table 1
Total dry weight, C concentration, N concentration, and C:N ratio of crops grown under ambient (357 μl l^{-1}) or elevated (750 μl l^{-1}) atmospheric CO_2 concentrations in 1992, 1993, and 1994[a]

	Sorghum				Soybean			
	Biomass (kg ha^{-1})	C (g kg^{-1})	N (g kg^{-1})	C:N (g g^{-1})	Biomass (kg ha^{-1})	C (g kg^{-1})	N (g kg^{-1})	C:N (g g^{-1})
1992								
Ambient	9423 a	429.6 a	7.8 a	55.6 a	5756 a	455.4 a	29.4 a	15.5 a
Elevated	11872 b	443.7 a	6.4 a	70.4 b	8296 b	453.1 a	27.0 b	16.8 a
Percentage of change	26	3	−18	27	44	−0.5	−8	8
1993								
Ambient	13254 a	414.8 a	7.7 a	54.1 a	9233 a	442.8 a	26.8 a	16.6 a
Elevated	16985 b	438.0 a	6.4 a	68.6 b	14086 b	440.3 a	24.2 b	18.2 a
Percentage of change	28	6	−17	27	53	−0.6	−10	10
1994								
Ambient	5696 a	435.7 a	9.4 a	42.2 a	9869 a	449.2 a	25.7 a	16.1 a
Elevated	7677 b	434.9 a	7.0 b	59.0 b	12086 b	448.9 a	24.9 a	16.9 a
Percentage of change	35	−0.2	−26	40	22	−0.1	−3	5

Biomass = total above and below ground plant organs; C = carbon concentration in the plant biomass; N = nitrogen concentration in the plant biomass; C:N = ratio of C to N in the plant biomass.

[a] Values represent means of three replications. Means within a column followed by the same letter do not differ significantly ($\alpha = 0.1$).

Prior et al., 1998; Rogers et al., 1999), which suggest that CO_2 enrichment will generally increase NUEF.

With soybean, a significant reduction was observed for N concentration in plant tissue for both 1992 and 1993 (similar trend was observed in 1994) (Table 1), as was noted for grain sorghum. While this is consistent with several studies which have found that elevated CO_2 results in reduced N concentration in plant tissue (Cotrufo et al., 1998; Prior et al., 1998), it varied from results reported by Allen et al. (1988) which reported no

Table 2
Fertilizer N content of grain sorghum grown under ambient (357 μl l^{-1}) or elevated (750 μl l^{-1}) atmospheric CO_2 concentrations in 1992, 1993, and 1994[a]

	Plant N (kg ha^{-1})	Fertilizer N plant (kg ha^{-1})	Fertilizer N soil (kg ha^{-1})	Total recovered fertilizer N (kg ha^{-1})	Plant fertilizer N efficiency (g g^{-1})	NUEF (g g^{-1})
1992						
Ambient	73.0 a	56.5 a	9.7 a	66.1 a	56.0 a	129 a
Elevated	75.3 a	54.4 a	9.9 a	64.3 a	53.9 a	158 b
Percentage of change	3	−4	2	−3	−4	22
1993						
Ambient	102.5 a	50.8 a	8.7 a	59.5 a	50.3 a	130 a
Elevated	108.9 a	48.6 a	6.7 a	55.3 a	48.2 a	157 b
Percentage of change	6	−4	−23	−7	−4	21
1994						
Ambient	53.9 a	45.5 a	22.7 a	68.2 a	45.1 a	108 a
Elevated	53.8 a	44.3 a	26.3 a	70.6 a	43.9 a	144 b
Percentage of change	−0.2	−3	16	4	−3	33

Fertilizer N plant = N in plant derived from fertilizer N application as determined through ^{15}N analysis; fertilizer N soil = N in soil derived from fertilizer N application as determined through ^{15}N analysis; total recovered fertilizer N = sum of fertilizer N in plant and soil; plant N efficiency = plant fertilizer N content per fertilizer N applied; nutrient utilization efficiency = unit of biomass produced per unit of N uptake.

[a] Values represent means of three replications. Means within a column followed by the same letter do not differ significantly ($\alpha = 0.1$).

Table 3
Fertilizer N content of soybean grown under ambient (357 μl l^{-1}) or elevated (750 μl l^{-1}) atmospheric CO_2 concentrations in 1992, 1993, and 1994[a]

	Plant N total (kg ha^{-1})	Plant N native soil (kg ha^{-1})	Plant N N_2 fixed (kg ha^{-1})	NUEF (g g^{-1})
1992				
Ambient	169.2 a	23.3 a	145.9 a	34 a
Elevated	224.2 b	21.4 a	202.8 b	37 a
Percentage of change	32	−8	39	9
1993				
Ambient	247.2 a	35.9 a	211.3 a	37 a
Elevated	339.3 b	33.7 a	305.6 b	41 a
Percentage of change	37	−6	45	11
1994				
Ambient	253.7 a	11.5 a	163.5 a	39 a
Elevated	301.7 b	9.6 a	198.6 b	40 a
Percentage of change	19	−16	21	3

Plant N native soil = N in plant that was derived from the soil as determined through ^{15}N analysis; plant N N_2 fixed = N in plant that was derived from atmospheric N_2 fixation as determined through ^{15}N analysis; nutrient utilization efficiency = unit of biomass produced per unit of N uptake.

[a] Values represent means of three replications. Means within a column followed by the same letter do not differ significantly ($\alpha = 0.1$).

change in plant N concentration over a wide range of atmospheric CO_2 growing conditions. However, elevated CO_2 resulted in a significant increase in N content for soybean in all 3 years, ranging from 19 to 37% under elevated CO_2 compared to ambient CO_2 (Table 3). Likewise (unlike grain sorghum), elevated CO_2 resulted in a significant increase in both total C content (biomass) and N content for soybean, which led to no significant change in C:N ratio due to CO_2 (Table 1). These results were consistent with those reported by Allen et al. (1988).

Soybean is a legume with symbiotic N_2-fixation capabilities involving *R. japonicum*. Other research has reported that high CO_2 conditions increased legume nodulation and biological N_2-fixation by legumes (Zanetti et al., 1996; Kimball et al., 2002). In this study, isotope dilution methods were used to measure the level of N_2-fixation by soybeans. The measured levels of N_2-fixation in soybean were significantly higher under elevated CO_2 compared to ambient CO_2 in all 3 years (Table 3). This increase in the level of biologically fixed N_2 in soybean accounts for the increased N levels observed in the elevated CO_2 treatment compared to ambient CO_2.

For both grain sorghum and soybean, a significant increase in residue biomass (root biomass and aboveground biomass−seed) was observed with elevated CO_2 during all 3 years of study (Table 4). Residue is defined as a measure of plant mass returned to the field after grain harvest. The residue that remains is not only the material that ultimately controls soil C level (as it decomposes), but it also directly impacts the soil N fertility (Hart et al., 1993).

With grain sorghum, the total N in residue was not significantly affected by CO_2 treatment, but because of the increased C content (residue biomass), the C:N ratio of the residue was significantly increased with elevated CO_2 compared to ambient CO_2 in 1993 and 1994 (similar trend in 1992) (Table 4). With soybean, much greater levels of total N in the residue were returned to the field compared to grain sorghum in all 3 years (Table 4). A significant increase in residue total N was also observed with the elevated CO_2 compared to ambient CO_2 in 1992 and 1993 (Table 4). However, because of the increased residue C (residue biomass), the C:N ratio of the residue was not significantly different between the elevated and ambient CO_2 treatments (Table 4).

Most N transformations in soil are regulated by microbial activity and organic matter content (Hart et al., 1993). A potential effect of crop growth under elevated CO_2 conditions may be an increased level of

Table 4
Residue total dry weight, N content, and C:N ratio of crops grown under ambient (357 $\mu l\,l^{-1}$) or elevated (750 $\mu l\,l^{-1}$) atmospheric CO_2 concentrations in 1992, 1993, and 1994[a]

	Sorghum			Soybean		
	Residue biomass (kg ha^{-1})	Residue total N (kg ha^{-1})	Residue C:N ratio (g g^{-1})	Residue biomass (kg ha^{-1})	Residue total N (kg ha^{-1})	Residue C:N ratio (g g^{-1})
1992						
Ambient	4729 a	17.8 a	116.3 a	4321 a	89.5 a	21.7 a
Elevated	6478 b	23.8 a	122.8 a	6153 b	104.2 b	26.8 a
Percentage of change	37	34	6	42	16	24
1993						
Ambient	7447 a	28.6 a	111.4 a	8143 a	189.7 a	18.9 a
Elevated	10303 b	33.0 a	136.2 b	12337 b	251.9 b	21.1 a
Percentage of change	38	15	22	52	33	12
1994						
Ambient	3190 a	16.2 a	85.4 a	7890 a	148.9 a	23.3 a
Elevated	4384 b	16.7 a	113.1 b	9420 b	153.0 a	27.2 a
Percentage of change	37	3	32	19	3	17

Residue biomass = sum of above ground plant tissue that would return to soil after harvest; residue total N = nitrogen content of the plant residue; residue C:N ratio = ratio of C concentration to N concentration in the plant residue.

[a] Values represent means of three replications. Means within a column followed by the same letter do not differ significantly ($\alpha = 0.1$).

organic carbon in soil which impacts N dynamics, including regulation of biological activity. For example, Gill et al. (2002) found that net N mineralization was decreased as a gradient of atmospheric CO_2 was increased in a grassland. Incubation studies using plant tissue grown under elevated CO_2 conditions indicated that N mineralization in soil may be reduced (Torbert et al., 1995, 1998; Prior et al., 1997). Similarly, soil samples taken from this study indicated that potential N mineralization could be reduced with elevated CO_2 (Torbert et al., 2001). Because of the economic and environmental consequences (both from nutrient balance and energy expenditures), assessing the impact of elevated CO_2 on N fertility is important.

In this study, stable isotopic techniques of ^{15}N were used to measure changes in N fertilizer interactions in the plant/soil system as affected by elevated CO_2 (Hauck and Bremner, 1976). These methods have been successfully used to measure changes in fertilizer N utilization as affected by soil water content (Torbert et al., 1992), tillage and traffic (Torbert and Reeves, 1994), and cover crops (Torbert et al., 1996a) in similar soils.

In grain sorghum, no significant effect of CO_2 treatment was observed for any of the fertilizer N measurements. No significant effect of CO_2 treatment was observed for fertilizer N uptake by grain sorghum plants in any of the 3 years of this study (Table 2). Likewise, no significant effect of CO_2 level was observed for N fertilizer remaining in the soil profile at the end of the growing season (Table 2). Therefore, there was no significant effect of CO_2 treatment for total recovered fertilizer N in the plant/soil system (Table 2). Consequently, there was no significant effect of CO_2 on fertilizer N efficiency for grain sorghum (Table 2), despite the 21–33% increase in NUEF. Similar results have been reported by Martin-Olmedo et al. (2002) with additions of ^{15}N enriched N fertilizer material to spring barley (*Hordeum disticum* L.). They reported that the overall ^{15}N content of plants grown in elevated CO_2 were not significantly different from plants grown in ambient CO_2, indicating that the difference observed with elevated CO_2 was due to increased root exploration. Likewise, Bassir-iRad et al. (1999) using ^{15}N techniques reported that elevated CO_2 made no significant difference in kinetic N uptake in soybean and grain sorghum plant species. Similarly, reports by Johnson et al. (2000) using ^{15}N techniques indicated that while there was no significant difference in the N dynamics from decomposition in litter bags containing needles from trees grown under elevated CO_2, the natural abundance of ^{15}N

was significantly greater with elevated CO_2 in both live and senesced needles, indicating a shift in uptake to different soil N pools.

The results of this study were consistent with research by Conroy et al. (1992) and Rogers et al. (1983a) which indicated that the critical N concentration for plant production (the concentration needed for maximum production) was decreased with elevated CO_2 concentration. In many cases, N sufficiency levels are used as a diagnostic tool to examine soil fertility conditions (Mills and Jones, 1996). For example, efforts have been made to develop plant fertilizer N needs based on N concentration in young corn plants or on the concentration of nitrate in corn stalks (Cerrato and Blackmer, 1991; Binford et al., 1992a,b). Changes in plant N concentrations due to elevated CO_2 may require revision of N fertilizer management practices (i.e. recommendations) based on plant N concentrations in a future elevated CO_2 environment (Rogers et al., 1996, 1999).

Likewise, fertilizer N recommendations are commonly based on yield goals of the specific crop to be produced. In this study, elevated CO_2 significantly increased biomass production (Table 1) (including grain yield components; Prior et al., 2003), with a large increase in the utilization of the available N as reflected in the significant increase in crop NUEF (Table 2). However, this increased utilization of N occurred with no apparent change in fertilizer N interactions in the plant/soil system, as reflected by the ^{15}N data (Table 2). As with the plant N concentration, these data indicate that fertilizer N recommendation based on yield goals may need to be changed in the future as CO_2 continues to rise. However, there was no evidence from this study that fertilizer N recommendations, based solely on soil test results, need to be altered. While increased additions of some nutrients may be needed to achieve the potential one-third increase in crop yields (Rosenzweig and Hillel, 1998), data from this study indicate that increased levels of N fertilizer may not be needed.

Clearly in this study, the C and N cycling was impacted by elevated CO_2 as was discussed in a review by Torbert et al. (2000). For example, measurement of nitrate levels below the rooting zone in this study indicated that nitrate leaching was reduced with elevated CO_2 treatment (Torbert et al., 1996b). Also, increased levels of soil C due to elevated CO_2 was observed with both the grain sorghum and the soybean (Torbert et al., 1997). While it is apparent from these studies that soil N cycling was substantially affected by elevated CO_2, there was no indication from the ^{15}N measurement taken in this study that these changes altered N fertility (Table 3). Even with the measured reduction of nitrate leaching with elevated CO_2 with grain sorghum, analysis of soil solution nitrate for ^{15}N content indicated that there was no significant difference in nitrate concentrations originating from fertilizer N application (Torbert et al., 1997).

The increased amounts of N returned to soil could increase the level of nitrate leaching (Goss et al., 1993). However, this was not observed to be the case in measurements of nitrate below the rooting zone in this study (Torbert et al., 1997). While the level of nitrate moving through the soil profile was increased with soybean compared to grain sorghum, a significant reduction in nitrate concentration was observed at several measuring points during the year for soybean grown under elevated CO_2 compared to ambient CO_2 (Torbert et al., 1997).

With soybean, there was a significant increase in total plant N content that matched the increase in biomass production in all 3 years of the study (Table 3). This increase was the result of an increased level of atmospheric N_2 fixation by soybeans under elevated CO_2, as measured by ^{15}N techniques (Table 3). The increased levels of photosynthate in the elevated CO_2 plants apparently stimulated the symbiotic fixation of atmospheric N_2. The increased plant N did not result from greater uptake of native soil N by soybeans, because no significant difference was observed for native soil N uptake in any year of the study (Table 3).

Since both the total biomass and the total N content were increased proportionally, unlike the grain sorghum, there was no significant difference in the calculated NUEF for soybean (Table 3). However, not only was the level of N produced in the grain sorghum increased, but also the level of N returned to the soil through crop residue was increased (Table 4). This increase could potentially impact the level of native soil N that is available to subsequent crops and potentially increase soil fertility, but was not observed during this 3-year study, as reflected by native plant N uptake. On the other hand, no impact of N uptake was observed for native soil N uptake during the study, which has been commonly speculated (Strain and Bazzaz, 1983).

4. Conclusions

Elevated atmospheric CO_2 increased total biomass production in all 3 years of both grain sorghum (average 30%) and soybean (average 40%). This increase was reflected in the amount of plant residue that was returned after harvest. With soybean, elevated CO_2 concentration greatly increased total N content (average 29%) of the plant biomass, but no impact to the plant C:N ratio was observed. This was due to the proportional increase in both atmospheric N_2 fixation and biomass production by soybean under elevated CO_2 conditions. With grain sorghum, total N uptake was not affected, but the C:N ratio was greatly increased (average 31%) by elevated CO_2 concentration. No impact of elevated CO_2 concentration was observed for fertilizer N in the plant/soil system with grain sorghum. This indicated that plants grown under elevated atmospheric CO_2 made better utilization of available N resources without impacting N management. This further suggests that future agro-ecosystems may be better adapted to limited resources (without limiting plant biomass production). The results from this study indicated that while crop production may be positively affected by increased atmospheric CO_2, substantial change in N soil fertility practices may not be required in sandy soil. However, N fertilizer recommendations based on plant N concentrations or yield goals may need to be adjusted to reflect changes in crop response resulting from increased atmospheric CO_2 concentration.

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