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Carbon Dioxide-Enriched Agroecosystems: Influence of Tillage on Short-Term Soil Carbon Dioxide Efflux

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ABSTRACT

Increasing atmospheric carbon dioxide (CO_2) concentration can increase biomass production that may influence carbon (C) dynamics in terrestrial ecosystems. Soil CO_2 efflux as affected by crop residues from high CO_2 environments managed under different tillage systems has not been explored. This study examined the effects of tillage systems in a legume {soybean [*Glycine max* (L.) Merr.]} and nonlegume {grain sorghum [*Sorghum bicolor*] (L.) Moench.} CO_2-enriched agroecosystem on the rates of short-term CO_2 evolution from a Blanton loamy sand (loamy siliceous, thermic Grossarenic Paleudults). In the spring of 1994, CO_2 efflux observations initiated within 5 s after a tillage event were compared to no-tillage conditions for 8 d in plots where both crop species had been grown in open top field chambers under two CO_2 conditions (ambient and twice ambient) for two seasons (1992 and 1993). Added CO_2 increased yields, residue, and root biomass; higher percent ground cover was also observed in CO_2-enriched plots prior to the tillage treatment. Differences in C/N ratio of the residue may have influenced CO_2 efflux rates; C/N ratio was highest for sorghum and was increased by elevated CO_2. Efflux patterns were characterized by flushes of CO_2 following initial tillage and rainfall events. Species × tillage and CO_2 × species interactions were noted on several days and for total CO_2 efflux values. Our results suggest that short-term CO_2 fluxes may be greater for tilled soybean and for soybean grown under elevated CO_2; however, short-term flux rates in the sorghum crop were affected by tillage, but not by CO_2 level. These short-term results should be viewed with caution when predicting long-term C turnover in agroecosystems.

The global C budget is not in balance (Houghton et al., 1990; Schlesinger, 1993). The chemical climate is changing and concentrations of trace gases in the atmosphere are continuously rising. Of special note is the increase in CO_2 (Keeling et al., 1989); it is the chief mobile form of C in the atmosphere and is a key player in the biosphere, geosphere, and hydrosphere (Holland, 1978; Bolin, 1986). The dynamics of C in terrestrial ecosystems has become a central question (Polglase and Wang, 1992) and there is much interest in the potential of highly managed agricultural soils to store surplus atmospheric CO_2 as an amelioration measure (Follet, 1993; Kern and Johnson, 1993). The rate of evolution of this stored soil C as a decomposition product, mainly CO_2, is an important aspect of net soil storage both in the short and long run.

Studies have clearly demonstrated that CO_2 enrichment can result in greater biomass production (Kimball, 1983; Strain and Cure, 1985; Rogers and Dahlman, 1993) and alterations in the chemical makeup of plant tissue, for example, C/N ratios (Conroy, 1992; Norby et al., 1986a; Norby et al., 1986b; Rogers et al., 1994). Elevated CO_2 has been shown to increase not only aboveground responses but also to increase root biomass (Rogers et al., 1992; Prior et al., 1994a; Prior et al. 1994b; Rogers et al., 1994; Prior et al., 1995). Increased roots may in turn influence C storage/cycling as well as belowground physicochemical and biological processes. Studies have shown that CO_2 enrichment often leads to higher tissue C/N ratios (Conroy, 1992; Owensby et al., 1993); crop residue C/N ratio is an important factor influencing rates of decomposition (Parr and Papendick, 1978; Blevins et al., 1984; Wood et al., 1994; Torbert et al., 1995). Changes in the quantity, as well as the quality, of plant tissue can affect decomposition processes that will affect nutrient and C turnover as well as soil properties. A consideration of these effects will become important in future residue management decisions, especially as more farms adopt conservation tillage systems.

The wide acceptance of conservation tillage systems results from the need to protect land resources while providing for the increasing demand for food and fiber in an economically attractive manner (Phillips et al., 1980). Conservation tillage can be used to maintain more surface residue that can aid in reducing wind damage to crops and soil erosion due to wind and/or water (Unger and McCalla, 1980; Griffith et al., 1986). This additional crop residue also can lead to improved soil structure due to higher organic matter (Campbell and Zentner, 1993), increased infiltration and water-holding capacity (Hudson, 1994), and a decrease in runoff by maintaining macropores and preventing soil surface sealing (Blevins et al., 1984; Griffith et al., 1986; Baker, 1991; Reeves, 1994). Although the use of these systems represent viable means of controlling CO_2 emission into the atmosphere and production cost by limiting the number of tillage operations (thereby decreasing fuel costs and machine wear), such advantages may be offset to some degree by the use and production of chemicals needed to control weeds, insects and plant diseases (Kern and Johnson, 1993). Recently, new data on the short-term flux of C as CO_2 from agroecosystems as affected by method of

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Abbreviations: CO_2, carbon dioxide; C, carbon; CDT, central daylight time; N, nitrogen.

tillage have been reported; conservation tillage results in lower CO_2 flux rates compared to various types of conventional tillage (Reicosky and Lindstrom, 1993). Such data suggest that adoption of conservation tillage may help reduce the emission of CO_2 to the atmosphere.

To date, no studies have addressed the effects of tillage practices on CO_2 flux rates from areas where crop residues were produced in a high CO_2 environment. In the following study, we explore the effects of spring tillage in two CO_2-enriched agroecosystems (soybean and sorghum) on the short-term rates of CO_2 evolution from the soil surface.

MATERIALS AND METHODS

Soybean ('Stonewall') and grain sorghum ('Savanna 5') plants were grown from seed to maturity in open top field chambers at two atmospheric CO_2 concentrations (ambient and twice ambient) for two growing seasons (1992 and 1993). In 1992, the mean seasonal daytime CO_2 concentrations were 357.5 $\pm$ 0.1 (SE) (ambient chamber) and 705.0 $\pm$ 0.3 $\mu L\ L^{-1}$ (enriched chamber). In 1993, the mean CO_2 concentrations were 364.0 $\pm$ 0.2 (ambient chamber) and 731.7 $\pm$ 0.4 $\mu L\ L^{-1}$ (enriched chamber).

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 and are described in detail by Rogers et al. (1983). 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 that was double-walled; the inside wall was perforated with 2.5-cm diam. holes to serve as ducts to distribute air uniformly into the chamber. Carbon dioxide concentrations were continually monitored (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).[1]

The experimental site was a soil bin located at the USDA-ARS National Soil Dynamics Laboratory, Auburn, AL. The bin is 2-m deep, 6-m wide, and 76-m long and was uniformly filled with surface soil of a Blanton loamy sand that had been continuously fallow for more than 25 yr (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 nitrogen (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).

Seeds were sown on 2 June and 5 May in 1992 and 1993, respectively. Soybean seeds were inoculated with commercial *Rhizobium* (Nitragin Co.) 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. To ensure adequate plant establishment, fertilizer N was broadcast at a rate of 34 kg N ha^{-1} to both the grain sorghum and the soybean shortly after planting (4 June 1992 and 6 May 1993). In the grain sorghum, an additional 67 kg N ha^{-1} was applied 30 d after planting (3 July 1992 and 7 June 1993). Weed control during the growing season was done by hand. In the off season, weed control was done both by hand and by use of glyphosate (*N*-[phosphonomethyl] glycine).

Plants within each chamber (i.e., delineated by a 3-m aluminum ring) were harvested at maturity for determination of top dry mass production (minus seed mass) and seed yield. Sorghum heads and soybean pods were removed from plants and processed through a plot combine; soybean pod hulls and sorghum chaff were added back to the appropriate study plots. Plant stalks were cut into approximately 15-cm lengths using hedge clippers and uniformly spread over the plots. To simulate seed loss during combining, 10% (by weight) 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 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. In addition, root samples were collected at physiological maturity by soil coring and a root extraction technique (Bohm, 1979). Twelve root-soil cores (2.4 mm diam., 30 cm length) were collected from each chamber. Roots were separated from soil with a hydropneumatic elutriation system (Gillison's Variety Fabrication, Inc., Benzonia, MI 49616) (Smucker et al., 1982) and organic debris were removed prior to dry weight determination (55°C). The root extraction technique used a manual winch (Model 527, Fulton, Milwaukee, WI) mounted onto a portable metal tripod with a cable gripping tool (Model 72285K8, Klein Tools, Chicago IL) attached to the plant stalk to break the roots from the soil; a scale (Model 8920, Hanson, Northbrook, IL) measured the peak force (load-kg $plant^{-1}$) required to uproot the plant (Prior et al., 1995). Root samples were collected from 12 and 16 plants per chamber in 1992 and 1993, respectively. Plants adjacent to pulled plants were not sampled in subsequent measurements. After soaking in water, root samples were washed free of soil using a soft bristle brush prior to drying (55°C) for dry weight determination. Root dry weights from each root sampling method were expressed on an area basis prior to being combined.

On 10 Apr. 1994, (DOY 100) two microplots (35 by 35 cm) were established within each chamber plot; tillage treatments (i.e., tillage and no-tillage plots) were randomly assigned to microplots. Up to this date, experimental plots had been managed under no-till conditions. To simulate a mechanical chisel plow tillage operation, a chisel plow tine was manually pulled across each tillage microplot three times (~ 10-cm apart) to a depth of 20 cm. Percent ground cover was determined for the entire surface area within all chambers using a line intersect method (Morrison et al., 1993) prior to initiating tillage treatments. Microplots under the no-tillage treatment were left undisturbed for the duration of the study. Soil CO_2 efflux and temperature measurements were made with a LI-COR 6400 gas exchange system equipped with a soil respiration chamber (Model 6000-09, LI-COR, Inc., Lincoln, NE); at each sampling, the tillage treatment measured first was selected at random. Carbon dioxide within the soil respiration chamber was scrubbed to a level below ambient (CO_2 level ca. 250 $\mu L\ L^{-1}$) and allowed to equilibrate for 1 min prior to initiation of the first measurement. Soil respiration rate was determined by the change in CO_2 concentration over a 60-s period; a duplicate reading was taken immediately following the first measurement. In the tilled microplots, initial measurements were made within 5 s of implementing the tillage treatment. For the first 2 d of the experiment, CO_2 efflux measurements were taken twice daily; readings were started at approximately 0900 and 1400 h Central Daylight Time (CDT) and are referred to with AM or PM designations (e.g., DOY 100 AM or DOY 100 PM). For the remaining 6 d, measurements were taken

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

only in the morning. Local weather data (rainfall, global radiation, and maximum and minimum air temperatures) were provided by the National Weather Service from a location approximately 0.5 km from the study site. Soil water content was gravimetrically determined on 15-cm soil cores taken midway between microplots on the first day and every other day thereafter except when rain was predicted and then soil samples were taken before and after rainfall events.

Additional soil samples were collected as described above for determination of soil C and N content. Soil samples were sieved (2-mm mesh) to remove residue fragments, ground with a roller grinder (Kelley, 1994) to pass a 1-mm mesh, and analyzed for total N and C content with a LECO CHN-600 C/N analyzer (LECO Corp., Augusta, GA). Subsamples of above- and belowground plant material for both growing seasons were prepared for C and N analysis using the same procedure.

The experiment was a split-plot design with three replicate blocks (6 by 25 m). Whole-plot treatments (plant species) were randomly assigned to half of each block. Subplot treatments (CO_2 levels) were randomly assigned to two open top chambers (3-m diam.) within each whole plot. Microplots treatments (tillage) were randomly assigned to one of two locations (35 by 35 cm) within each open top chamber and represented an additional split-plot treatment. Statistical analyses of data were performed using the General Linear Model (GLM) procedure of SAS (Statistical Analysis Systems, 1982). Appropriate error terms were specified for each split-plot treatment. Contrast statements were used to determine the significance between interacting main effect variables. Differences were considered significant at the $P < 0.10$ level. Values that differed at the $0.10 < P < 0.20$ level were considered trends.

RESULTS AND DISCUSSION

Dry Matter Production

The effect of changing CO_2 level on dry matter production for two growing seasons prior to initiation of this study are shown in Table 1. The observed positive seed yield response due to CO_2 enrichment are in general agreement with other reports (Kimball, 1983; Rogers and Dahlman, 1993; Wittwer, 1995). In 1992, both species responded to changing CO_2 levels in similar ways. However, a significant $CO_2 \times$ species interaction occurred in 1993; there was a greater percentage increase in yield and residue (i.e., minus seed dry mass) for the C_3 soybean relative to the C_4 sorghum under CO_2-enriched conditions. Root mass increased due to elevated CO_2 for both species; no $CO_2 \times$ species interaction was detected in either year. In 1992, both residue and root biomass were higher for soybean, but in 1993 an opposite pattern was observed wherein sorghum residue and root biomass were higher. Sorghum grain yield was higher than soybean in both years. Overall, increases in the cumulative amount of biomass returned to the soil surface and subterranean environment may impact decomposition processes thereby influencing soil CO_2 efflux in agroecosystems. This aspect is especially important when the quantity of biomass produced is considered in combination with changes in litter quality (Melillo, 1983).

Chemical Analysis of Plant Components

Results of laboratory analysis of residue and root material are shown in Tables 2 and 3, respectively. No significant $CO_2 \times$ species interactions were found for C or N content of residue and root components in either year. The C content for both plant parts did not differ between species or CO_2 treatment in 1992; however, in 1993, C content of plant parts varied between CO_2 and/or species, but these differences were not large. The N content in residue and root components was reduced under CO_2-enriched conditions, a finding which is in agreement with several other studies (Conroy, 1992; Owensby et al., 1993; Amthor et al., 1994; Torbert et al., 1995). Species differences in N content were also detected with soybean being consistently higher than

Table 1. The effect of carbon dioxide (CO_2) concentration on grain, residue (aboveground dry mass minus grain mass), and root dry mass for sorghum and soybean in 1992 and 1993. Means and probabilities shown.

Variable, g m^{-2}	CO_2 µmol mol^{-1} 360	720	Pr > F†	Species Soybean	Sorghum	Pr > F	Interaction Pr > F $CO_2 \times$ Species
			1992				
Grain	315.47	392.18	<0.01	293.84	413.82	<0.01	0.34
Residue	462.91	548.72	0.02	621.75	389.89	<0.01	0.38
Root	165.26	232.20	0.01	242.59	154.87	0.02	0.20
			1993				
Grain	275.46	358.53	<0.01	216.30	417.70	<0.01	0.02
Residue	402.70	591.20	<0.01	403.47	590.43	0.04	0.02
Root	191.48	250.21	0.01	192.46	249.23	0.05	0.27

Variable‡	Year	CO_2	Species	Mean	Pr > F Contrast	Contrast
Residue	1993	360	Soybean	290.35	<0.01	360 vs. 720
		720	Soybean	516.59		
		360	Sorghum	515.04	<0.01	360 vs. 720
		720	Sorghum	665.81		
Grain	1993	360	Soybean	162.07	<0.01	360 vs. 720
		720	Soybean	270.52		
		360	Sorghum	388.86	<0.01	360 vs. 720
		720	Sorghum	446.54		

† Probability of a greater F value by chance for difference between the CO_2 or species treatment.
‡ Variable where the interaction was significant.

Table 2. The effect of CO_2 concentration on residue total carbon (C), total nitrogen (N), and C/N ratio for sorghum and soybean in 1992 and 1993. Means and probabilities shown.

Variable	CO_2, μmol mol^{-1} 360	720	Pr > F†	Species Soybean	Sorghum	Pr > F	Interaction Pr > F CO_2 × Species
			1992				
C, g kg^{-1}	420.32	421.23	0.90	416.85	424.70	0.36	0.88
N, g kg^{-1}	9.68	7.92	0.01	13.10	4.50	0.01	0.94
C/N	56.22	77.16	0.07	33.64	99.74	0.01	0.09
			1993				
C, g kg^{-1}	428.73	430.62	0.06	426.98	432.37	0.01	0.78
N, g kg^{-1}	10.77	10.00	0.08	15.37	5.40	0.01	0.78
C/N	51.11	57.92	0.03	27.90	81.13	0.01	0.06

Variable‡	Year	CO_2	Species	Mean	Pr > F Contrast	Contrast
C/N	1992	360	Soybean	32.78	0.90	360 vs. 720
		720	Soybean	34.50		
		360	Sorghum	79.66	0.03	360 vs. 720
		720	Sorghum	119.81		
C/N	1993	360	Soybean	27.31	0.71	360 vs. 720
		720	Soybean	28.50		
		360	Sorghum	74.92	0.01	360 vs. 720
		720	Sorghum	87.35		

† Probability of a greater *F* value by chance for difference between the CO_2 or species treatment.
‡ Variable where the interaction was significant.

sorghum; across both years, soybean N content for residue and root material was 170 and 220% greater than its sorghum counterparts, respectively. This finding was not surprising since soybean fixes atmospheric N.

The lower tissue N concentration of sorghum resulted in much higher C/N ratios relative to soybean plant parts. Previous work has shown that legume residues generally have lower C/N ratios compared to nonlegume plant species (Smith and Sharpley, 1990; Reeves, 1994). Shifts in residue quality, such as C/N ratio, influence the ability of soil microbes to decompose crop residues; differences in levels of N mineralization (threefold or greater) as affected by crop residue type have been shown to occur in the general order of alfalfa > peanut > soybean > oat ≥ sorghum > wheat > corn [*Medicago sativa* L., *Arachis hypogaea* L., *Glycine max* (L.) Merr., *Avena sativa* L., *Sorghum bicolor* (L.) Moench, *Triticum aestivum* L., *Zea mays* L., respectively] (Smith and Sharpley, 1990).

Residues under elevated CO_2 also had higher C/N ratios; a trend was also observed for roots in 1993. Significant CO_2 × species interactions were observed in both years for residue (Table 2) and a similar trend occurred for root material in 1993 (Table 3) with increased C/N ratios due to CO_2 enrichment restricted to sorghum plant parts. Increased C/N ratios of stems and leaves of cotton grown under CO_2-enriched conditions have been reported; this ratio also tended to be higher for root tissue (Torbert et al., 1995). Owensby et al. (1993) reported higher C/N ratios for above- and belowground plant components in a tallgrass prairie under CO_2-enriched conditions. Other elevated CO_2 studies have reported higher C/N ratios for leaf litter in some cases (Norby et al., 1986b) but not in others (Curtis et al., 1989).

Experimental Plot Characteristics Prior to Tillage

Results from chemical analysis of soil samples taken prior to the tillage treatment (and CO_2 efflux measurements) indicated fewer differences between whole plots regardless of CO_2 and species treatment combinations

Table 3. The effect of CO_2 concentration on root total carbon (C), total nitrogen (N), and C/N ratio for sorghum and soybean in 1992 and 1993. Means and probabilities shown.

Variable	CO_2, μmol mol^{-1} 360	720	Pr > F†	Species Soybean	Sorghum	Pr > F	Interaction Pr > F CO_2 × Species
			1992				
C, g kg^{-1}	416.17	437.17	0.56	436.33	417.00	0.46	0.56
N, g kg^{-1}	5.32	4.45	0.05	7.45	2.32	<0.01	0.17
C/N	108.35	132.66	0.25	59.61	181.40	0.01	0.69
			1993				
C, g kg^{-1}	407.27	418.95	0.44	419.68	406.53	0.03	0.43
N, g kg^{-1}	7.47	6.27	0.15	10.75	2.98	<0.01	0.82
C/N	77.28	107.31	0.12	39.91	144.67	<0.01	0.19

† Probability of a greater *F* value by chance for difference between the CO_2 or species treatment.
‡ Variable where the interaction was significant.

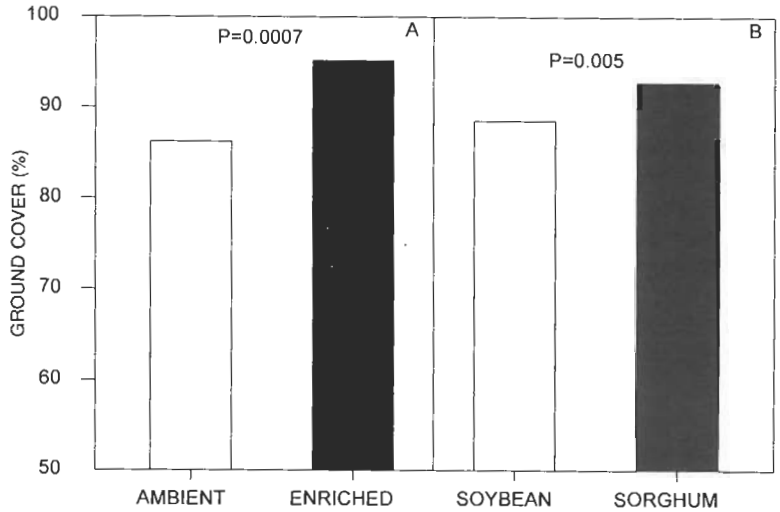

Fig. 1. The average percent ground cover at time of tillage initiation for ambient and enriched CO_2 treatments (*A*) and for soybean and sorghum (*B*). Means and probabilities are shown.

(data not shown). The C and N content averaged about 2.5 and 0.3 g kg^{-1}, respectively. No differences in C/N ratios were observed (average value of about 9). After three seasons of CO_2 enrichment and added N in a tallgrass prairie system, Rice et al. (1994) reported upward shifts in C and N content at a depth of 5 to 15 cm, but not at 0 to 5 cm. Our soil analysis was of samples collected from a depth of 0 to 15 cm that precluded detection of possible changes in C and N content at other depth increments.

Percent ground cover determined before implementation of the tillage treatment is shown in Fig. 1. The increase in residue production that occurred under elevated CO_2 conditions (Table 1) resulted in greater percent ground coverage after two growing seasons in study plots for both species (Fig. 1A). A significant species effect was observed with more surface coverage occurring in sorghum plots relative to soybean plots (Fig. 1B). These findings agree with other reports (Griffith et al., 1986).

Weather

Weather data during the 8-d measurement period of CO_2 efflux are shown in Fig. 2. The ranges of average daily maximum and minimum temperatures were 39.4 to 47.2°C and 25.6 to 35.6°C, respectively (Fig. 2A). The soil temperature at time of CO_2 efflux measurements ranged from about 25 to 35°C (data not shown). Daily total global radiation ranged from 9.5 to 28 MJ m^{-2} d^{-1} with most values being above 20 MJ m^{-2} d^{-1} (Fig. 2B); the two lowest values coincided with the two rainfall events on DOY 103 and 106 (15.5 and 26.2 mm of precipitation, respectively; Fig. 2C). Soil water content prior to rainfall events averaged 0.05 kg kg^{-1} while readings following rain events averaged about 0.08 kg kg^{-1} (data not shown).

Treatment Effects on Soil Carbon Dioxide Efflux

Soil CO_2 efflux was often significantly influenced by CO_2, crop species, and tillage treatments. In general, no significant CO_2 × tillage or CO_2 × species × tillage interactions occurred during the 8 d of measurement. One exception did occur on DOY 103, where a CO_2 × tillage interaction was detected; in this case, the CO_2-enriched microplots under tilled conditions had higher soil CO_2 efflux values relative to their ambient counterparts (P = 0.04; data not shown). The overall lack of such interactions indicated that experimental plots (previously cropped with either plant species under ambient and CO_2-enriched conditions) responded to tillage similarly. However, significant two-way interactions (i.e., tillage × species and CO_2 × species) were detected (Fig. 3) and are discussed below.

Tillage, Species, and Interactive Effects on CO_2 Efflux

The tillage and species treatments and their interaction influenced the rate of soil CO_2 efflux during the sample period (Fig. 3A). In most cases, soybean microplots had higher efflux rates relative to sorghum microplots. Under tilled conditions, higher CO_2 efflux values were observed relative to no-till conditions ($P \leq 0.02$), except on DOY 106; a similar trend occurred on DOY 103 (P = 0.15). Total CO_2 efflux from tilled plots significantly exceeded those observed under no tilled conditions for both species (Table 4). Significant tillage × species interactions were noted at several samplings (DOY 100 and 101 PM and 103–104; $P \leq 0.05$) with a similar trend observed at two samplings (DOY 101 AM, P = 0.16 and 105, P = 0.18). In these cases, tilled soybean microplots had higher CO_2 efflux values relative to tilled sorghum microplots (Fig. 3A). Total CO_2 efflux for tilled soybean microplots was greater than for tilled sorghum microplots ($P <$ 0.01), thus suggesting that the quality of soybean residue, in terms of lower C/N ratios, represented a more readily available substrate for microbial use. Hendrix et al. (1988) found that plots with a legume cover crop (clover) had higher CO_2 efflux rates compared to plots with rye as the cover crop.

During the 8-d period, wide variation in soil CO_2 efflux rates was observed (Fig. 3A). Tillage initially

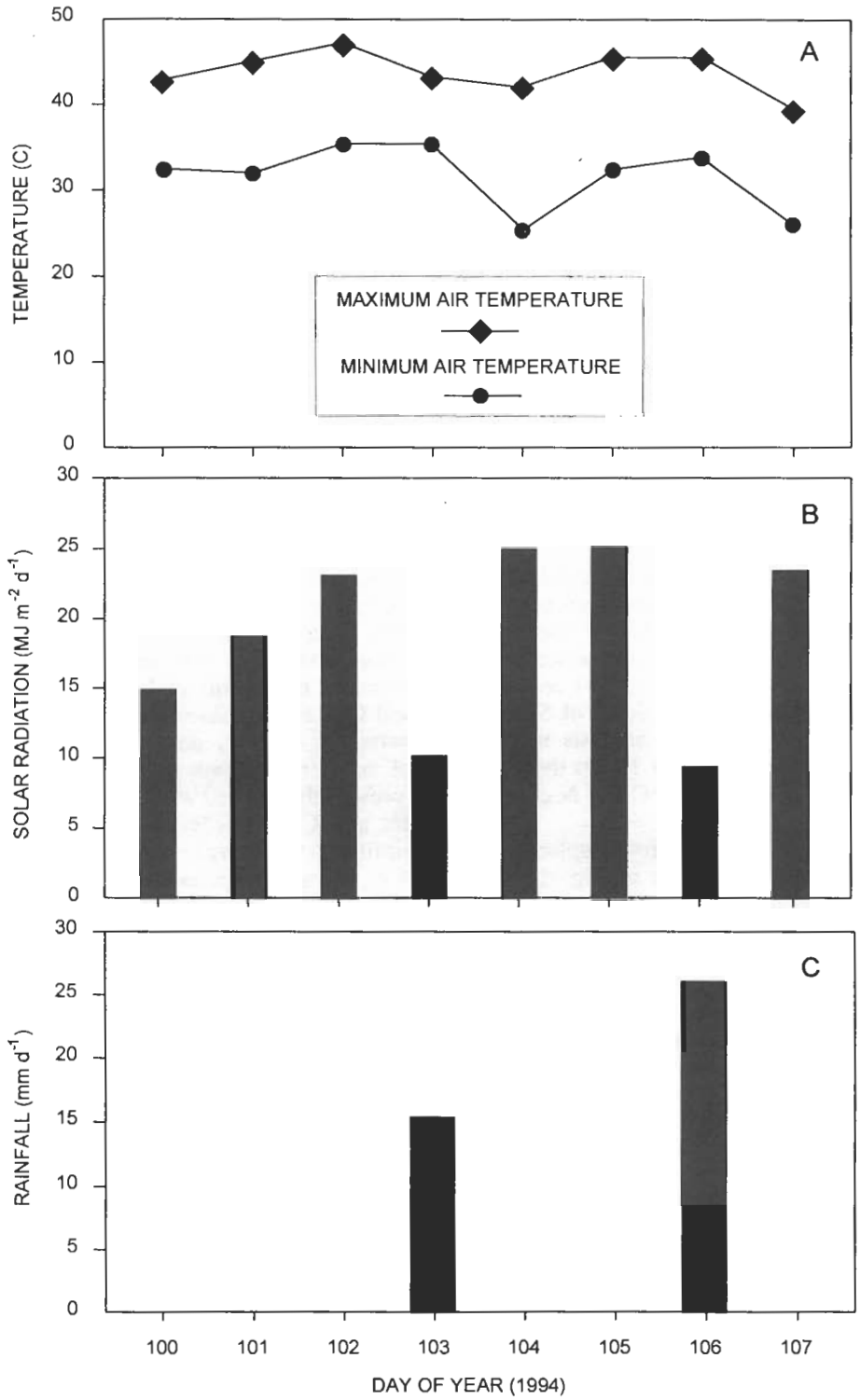

Fig. 2. The maximum and minimum air temperature (*A*), solar radiation (*B*), and rainfall (*C*) during the sampling period.

resulted in a large efflux of CO_2 for both species with rates of CO_2 efflux dropping off in a linear fashion for the next few days. The immediate increase in CO_2 efflux probably reflects the release of CO_2 from soil pores and increased microbial activity due to residue incorporation. These observations are in agreement with findings of others using a gas exchange system (Reicosky and Lindstrom, 1993). In contrast, Hendrix et al. (1988) reported that under different crop/soil systems the predicted pulse in CO_2 flux immediately following tillage was not detected, or was missed by their measurement technique (static-absorption technique); a finding supported by Buyanovsky et al. (1986) using the same technique. However, these investigators detected increases in CO_2 flux about 7 d (Hendrix et al., 1988) and 14 d (Buyanovsky et al., 1986) after initial tillage events, suggesting a delay

Table 4. Total soil CO_2 efflux (mol m^{-2}) as affected by interactions among treatment variables; CO_2 × species and tillage × species interactions are shown.

Species	CO_2 µmol mol^{-1} 360	720	Pr > F† contrast	Tillage No-till	Tilled	Pr > F contrast
Soybean	1.0115	1.2231	0.03	0.9474	1.2872	<0.01
Sorghum	0.9151	0.8794	0.68	0.8295	0.9650	0.07

† Probability of a greater *F* value by chance for difference.

between tillage and increased soil microbial activity. Hendrix et al. (1988) proposed a two-phase scenario to describe CO_2 flux patterns following tillage. This scenario included a rapid efflux of CO_2 following incorporation of residue that may result in mineralization of recently exposed labile compounds (a pattern that may not have been detected in their study), followed by a phase of CO_2 flux associated with incorporated residue being colonized and decomposed by the microbial community. We suggest the rapid efflux of CO_2 may be due to release of CO_2 from soil pores in addition to mineralization of recently exposed labile compounds.

Our study also showed pulses in CO_2 efflux over the remaining sample period associated with rainfall events (Fig. 2C). Several studies have found that abiotic factors such as soil water content and temperature are important in relation to patterns of CO_2 evolution from the soil (Buyanovsky and Wagner, 1983; Buyanovsky et al., 1986; Hendrix et al., 1988). For example, Buyanovsky and Wagner (1983) reported that CO_2 concentration was most influenced by soil temperatures above 15°C, while the influence of soil water content was most evident at soil temperatures greater than 10°C. In our study, soil temperature varied between 25 to 35°C and two significant rainfall events occurred during the 8-d measurement period. Following rainfall events on DOY 103 and DOY 106, CO_2 efflux values returned to the initial level or

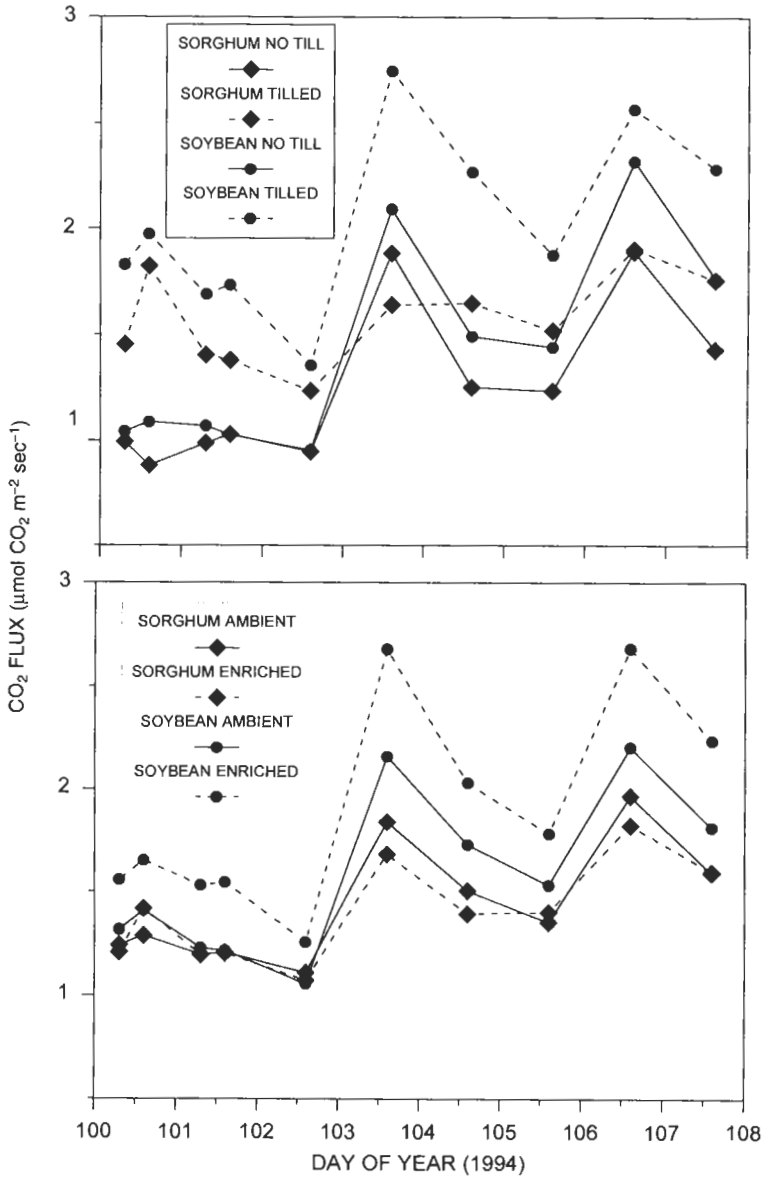

Fig. 3. Carbon dioxide efflux rates over an 8-d period following a tillage event for plots cropped with soybean or sorghum for two growing seasons: (*A*) averaged across CO_2 treatment; (*B*) averaged across tillage treatment.

higher, depending on treatment combination, and then decreased in a manner similar to that observed after tillage. In contrast, Reicosky and Lindstrom (1993) reported a temporary depression in CO_2 flux rate (i.e., for a few days) for tilled plots due to rainfall; after 3 d, flux rates increased and then began to fall in a fashion like that as observed after the initial tillage event. However, they also noted that the peak values after rainfall were substantially lower compared to measures taken immediately following tillage. Differences in CO_2 flux observed between Reicosky and Lindstrom (1993) and our study may have been related to different soil series (e.g., porosity and infiltration) and/or the impact of rainfall events on soil surface crust formation.

Atmospheric Carbon Dioxide, Species, and Interactive Effects on Carbon Dioxide Efflux

The CO_2 and species treatments and their interaction often influenced CO_2 efflux from the soil (Fig. 3B). As previously described, there were three distinct phases of CO_2 efflux from the soil; the first was associated with initiation of the study (i.e., tillage), while the other two were related to rainfall events. The interactive effects of CO_2 level and species were significant on many days (i.e., DOY 101–103 and 106–107, $P \leq 0.07$). In all cases, enriched soybean microplots had significantly higher CO_2 efflux rates relative to their ambient counterparts; similar trends were also noted on other days (i.e., DOY 100 and 104; $P = 0.17$). Total CO_2 efflux values were significantly greater for soybean under CO_2-enriched conditions (Table 4). No differences in CO_2 efflux rates over the sample period or in total efflux values were observed between ambient and CO_2-enriched sorghum microplots.

Differences in CO_2 efflux rates observed between soybean and sorghum microplots as affected by CO_2 level probably reflects changes in both the quantity and quality of biomass input to the soil system. Data from the previous growing seasons clearly demonstrated that CO_2 enrichment increased the above- and belowground biomass fractions for both species (Table 1), while shifts in C/N ratios were mainly restricted to sorghum (Table 2). Despite the higher biomass inputs for sorghum under CO_2-enriched conditions, the CO_2-induced increase in C/N ratios of tissue probably limited decomposition, thus CO_2 efflux rates were similar to ambient plots (Fig. 3B). Studies conducted in tall grass prairie systems have found that CO_2 enrichment results in higher C/N ratios of above- and belowground plant components (Owensby et al., 1993) and increases microbial biomass N, which suggests that the decomposition rate of plant litter may be reduced due to the N requirement of microbes to complete decomposition (Owensby et al., 1994). Furthermore, Owensby et al. (1994) found that added N enhanced microbial activity (i.e., increased microbial biomass C and N) under elevated CO_2 which indicated that not only was N limiting microbial activity, but could ultimately impact plant available N. Torbert et al. (1995) found greater net N immobilization during laboratory incubation of various soil series with added plant residue (i.e., leaf, stem, and roots) which had been grown under CO_2 enrichment. Similarly, Wood et al. (1994) found (during a 30-d incubation) that an N limitation for soil from CO_2-enriched plots was indicated by increased N immobilization that limited potential C mineralization and C turnover. However, the same may not be true for soybean. The CO_2-induced increase in biomass production in combination with the much lower C/N ratio of soybean tissue probably translated into greater N availability to soil microbes that resulted in the higher CO_2 efflux rates observed in CO_2-enriched soybean plots (Fig. 3B).

CONCLUSIONS

Several hypotheses have been put forth concerning the issue of C storage in terrestrial ecosystems as atmospheric CO_2 increases worldwide. Several researchers have postulated that C storage in terrestrial systems may occur due to the higher plant productivity observed under CO_2-enriched conditions (Tans et al., 1990; Allen, 1990; Lekkerkerk et al., 1990; Rogers et al. 1994). Results from this study suggest that efflux of CO_2 from soil may depend on crop species and tillage practice. Our data, although short-term, suggest that less soil CO_2 efflux may occur under sorghum cropping systems; however, this efflux may be enhanced under standard tillage practices. On the other hand, soybean crops may have higher rates of CO_2 flux due to factors such as lower C/N ratios (relative to sorghum) suggesting that much of the added C in these agronomic systems could be returned to the atmosphere, particularly under tilled conditions. These short-term results point to the potential for agronomic management practices to influence C storage and, thus, the role of these ecosystems in ameliorating the rising level of atmospheric CO_2. Obviously, these data are of too short a duration to make these predictions with confidence and more in-depth studies are needed regarding CO_2 flux patterns/C storage over the long term in agroecosystems.

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