Effects of Elevated CO_2 and Agricultural Management on Flux of Greenhouse Gases From Soil

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Abstract: To evaluate the contribution of agriculture to climate change, the flux of greenhouse gases from different cropping systems must be assessed. Soil greenhouse gas flux (CO_2, N_2O, and CH_4) was assessed during the final growing season in a long-term (10-year) study evaluating the effects of crop management (conservation and conventional) and atmospheric CO_2 (ambient and twice ambient) on a Decatur silt loam (clayey, kaolinitic, thermic Rhodic Paleudults). Seasonal soil CO_2 flux was significantly greater under elevated (4.39 Mg CO_2-C ha^{-1}) versus ambient CO_2 (3.34 Mg CO_2-C ha^{-1}) and was generally greater in the conventional (4.19 Mg CO_2-C ha^{-1}) compared with the conservation (3.53 Mg CO_2-C ha^{-1}) system. Soil flux of both N_2O (range, −1.5 to 53.4 g N_2O-N ha^{-1} day^{-1}) and CH_4 (range, −7.9 to 24.4 g CH_4-C ha^{-1} day^{-1}) were low throughout the study and rarely exhibited differences caused by treatments. Global warming potential (calculated based on flux of individual gases) was increased by elevated CO_2 (33.4%) and by conventional management (17.1%); these increases were driven primarily by soil CO_2 flux. As atmospheric CO_2 continues to rise, our results suggest adoption of conservation management systems represents a viable means of reducing agriculture's potential contribution to global climate change.

Key words: Carbon dioxide, global change, greenhouse gases, methane, nitrous oxide

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The level of carbon dioxide (CO_2) in the atmosphere has increased from approximately 280 ppm at the beginning of the industrial revolution to approximately 380 ppm today primarily because of fossil fuel burning and land use change (Keeling and Whorf, 2001), resulting in increased attention to the global carbon (C) cycle. Approaches for mitigating the increase in atmospheric CO_2 are being proposed. One such method is the storage of C in agricultural soils (Kern and Johnson, 1993; McCarl and Schneider, 2001; West and Post, 2002). Research by our group and others (Amthor, 1995; Torbert et al., 2000; Prior et al., 2005) has shown that soil C storage is generally increased under elevated atmospheric CO_2 primarily because of increased biomass production. Although increased storage of C can enhance soil quality, the stability of this C as well as the impact of elevated CO_2 and land management practices on the emissions of greenhouse gases (GHG) need to be addressed to fully understand the contribution of agriculture to climate change in the future.

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) are important GHG potentially contributing to global climate change. Animal and crop production may account for as much as 70% of annual global anthropogenic N_2O emissions and about 33% of global CH_4 emissions, with these agricultural emissions projected to increase (Mosier et al., 1998; Mosier, 2001). A more detailed accounting of natural and anthropogenic N_2O and CH_4 sinks and sources has recently been published (US EPA, 2010). Given the potential of these GHG to contribute to global climate change, impacts of management and environmental factors on their flux from soils have begun to be more intensively assessed. Cultivation and application of fertilizer N have been shown to inhibit CH_4 oxidation in soil (Mosier et al., 1991, 1996; Kessavalou et al., 1998; Khalil and Baggs, 2005). Kessavalou et al. (1998) found that CH_4 and N_2O flux from agricultural soils increased following tillage events and suggested that no-tillage systems represented a lower threat to deterioration of both atmospheric and soil quality. Li et al. (2005) found that farmyard manure application increased C sequestration while increasing N_2O emissions with little impact on CH_4 emissions. For 20 years, increased N_2O emissions from this system offset C sequestration from 75% to 310%, depending on the land management practice. However, Parkin and Kaspar (2006) found no differences in N_2O emissions between different management systems in a corn-soybean rotation. Johnson et al. (2007) concluded that agricultural practices such as reduced tillage will increase soil organic C and potentially enhance CH_4 consumption, imparting a net positive impact on the emissions of GHG despite increased emissions of N_2O observed in no-till systems.

In addition to land management practices, elevated atmospheric CO_2 has been shown to increase emissions of GHG. Elevated atmospheric CO_2 generally increases soil CO_2 flux in the range of 15% to 50% (Nakayama et al., 1994; Verburg et al., 1998; Zak et al., 2000). This increased soil CO_2 flux can be caused by effects of elevated CO_2 on autotrophic (i.e., plants) (Nakayama et al., 1994; Vose et al., 1997; Zak et al., 2000) and/or heterotrophic (i.e., soil microbes) (Nakayama et al., 1994; Vose et al., 1997; Zak et al., 2000) respiration.

In addition to soil CO_2 flux, elevated atmospheric CO_2 can impact CH_4 and N_2O flux. Cheng et al. (2006) reported a 58% increase in CH_4 flux from rice paddies under elevated CO_2. This increase was attributed to greater root exudates and numbers of tillers, resulting in more surface area for the release of CH_4 to the atmosphere (Ziska et al., 1998; Inubushi et al., 2003). However, Chan and Parkin (2001b) reported that when exposed to elevated concentrations of atmospheric CH_4, well-drained agricultural soils may become CH_4 sinks. Nitrous oxide flux was not affected by elevated CO_2 in the rice study by Cheng et al. (2006). However, Kettunen et al. (2006) showed that elevated CO_2 increased both N_2O flux from soil and soil water content.

These variable findings demonstrate that agriculture may act as a source or a sink for GHG under conditions of elevated CO_2. This, as well as their impact on global climate, demonstrates a need to evaluate GHG fluxes under different land use and soil management practices. Furthermore, many previous studies evaluating soil GHG flux have been conducted in short-term field trials. Therefore, there is a need to measure GHG flux from long-term studies under different land management practices and at different levels of atmospheric CO_2. The objective

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of the current study was to evaluate the flux of GHG (CO_2, N_2O, and CH_4) from conventional and conservation management systems that had been under the influence of elevated atmospheric CO_2 for 10 years.

MATERIALS AND METHODS

The experiment was conducted at the outdoor soil bin facility located at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL (32.6°N, 85.5°W) in a bin (7 × 76 × 2 m deep) filled with a Decatur silt loam soil (clayey, kaolinitic, thermic Rhodic Paleudults). The soil bin facility was constructed in the mid-1930s, and the soil bins have since been primarily used for the development and testing of new agricultural machinery; thus, they were kept mechanically fallow throughout most of their history. The uniformity of these bins provide for a much more homogeneous soil, leading to more consistent plant growth patterns than found in a typical field setting.

Crops within the soil bin were grown from seed to maturity in open-top chambers (OTC) (Rogers et al., 1983) under ambient and elevated atmospheric CO_2 levels in two different crop management systems (conventional and conservation). Carbon dioxide was supplied from a 12.7 Mg liquid CO_2 receiver through a high-volume dispensing manifold. Atmospheric CO_2 concentration was elevated by continuous injection of CO_2 into plenum boxes as detailed in Mitchell et al. (1995). Carbon dioxide concentrations were continually monitored (24 h day^{-1}) using a time-shared manifold with samples drawn through solenoids to an infrared CO_2 analyzer (Model 6252; LI-COR, Inc, Lincoln, NE). The mean daytime CO_2 concentrations were 375.39 ± 0.07 μLL^{-1} (SE) (n = 109,562; ambient CO_2 treatment) and 683.27 ± 0.23 μLL^{-1} (SE) (n = 109,591; elevated CO_2 treatment). The target concentration for the elevated CO_2 treatment was 720 μLL^{-1}. The only downtime for CO_2 exposure was associated with tillage and planting operations as described later.

This report reviews soil-atmosphere GHG flux (CO_2, CH_4, N_2O) in the final growing season of a 10-year elevated CO_2 study (1997–2007) comparing two crop management systems (conventional and conservation). These crop management and crop rotation sequences have been previously described in detail (Prior et al., 2005; 2010). Briefly, the conventional system used a grain sorghum [*Sorghum bicolor* (L.) Moench. "Pioneer 8282"] and soybean [*Glycine max* (L.) Merr. "Asgrow 6101"] rotation with spring tillage and winter fallow. To simulate spring tillage operations in this system, the following procedures were used: (i) a pitchfork was inserted (10 cm between insertion points) to a depth of 20 to 25 cm before heaving the soil to simulate a chisel plow operation; (ii) a large push-type PTO tiller (Model 192432; Gardenway Inc, Troy, NY) was operated twice to a soil depth of 15 to 20 cm to simulate two disking operations; and (iii) a small push-type garden cultivator (Model 410R; Ryobi Technolgies Inc, Anderson, SC) was operated to a soil depth of 8 to 10 cm to simulate a field cultivation operation. In the conservation system, grain sorghum and soybean were also rotated with three cover crops in the order of crimson clover (*Trifolium incarnatum* L. "AU Robin"), sorghum, sunn hemp (*Crotalaria juncea* L. "Tropic Sunn"), wheat (*Triticum aestivum* L. "Pioneer 2684"), and soybean. The conservation system used "no-tillage" practices with no fallow periods. In both management systems, row crop seeds were sown (20/m of row) on 0.38-m row spacings using a hand-operated precision garden seeder (Model 1001-B; Earthway, Bristol, IN). To ensure adequate plant establishment and grain production for sorghum and wheat, fertilizer N (ammonium nitrate) was broadcast applied in split applications. For grain sorghum, fertilizer N was applied at a rate of 34 kg N ha^{-1} shortly after planting, and an additional 101 kg N ha^{-1} was applied 30 days after planting. For wheat, fertilizer N was applied at planting (34 kg N ha^{-1}), 3.5 months after planting (67.4 kg N ha^{-1}), and 4.5 months after planting (34 kg N ha^{-1}). Because clover, soybean, and sunn hemp are nitrogen fixers, they received no fertilizer N; however, seeds were inoculated with commercial Rhizobium (Nitragin Co, Milwaukee, WI) before planting. Cover crops and sorghum were terminated with glyphosate (N-[phosphonomethyl] glycine) 10 days before planting the following crop to prevent regrowth. All operations previously described were also conducted on all nonexperimental areas to ensure uniform treatment of areas bordering the study plots. Rainfall was measured on-site throughout the study period.

Soil flux measurements were taken in the final soybean crop using custom-made trace gas flux chambers constructed according to the GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement Network) chamber-based trace gas flux measurement protocol (Parkin and Kaspar, 2006). Two polyvinylchloride rings (25.4-cm diameter × 10.2-cm tall) were installed between rows in each plot to a depth of approximately 5.1 cm. These rings served as bases for flux chambers and were left in place throughout the experiment unless they needed to be removed for tillage and planting. Midday flux measurements were conducted approximately every other week by sealing vented chambers (25.4-cm diameter × 11.4-cm tall) onto the rings before collecting gas samples at 0, 15, 30, and 45 min after chamber closure. Chambers are constructed from polyvinylchloride and covered with reflective tape. At each time point for sampling, gas samples (10 mL) were collected with polypropylene syringes and immediately injected into evacuated glass vials (6 mL) fitted with butyl rubber stoppers as described by Parkin and Kaspar (2006). The overpressure facilitates subsequent removal of the gas sample for analysis. Samples were then injected into a Shimadzu GC-2014 gas chromatograph (Shimadzu Scientific Instruments, Inc, Columbia, MD) containing three detectors: a thermal conductivity detector for CO_2 analysis; an electrical conductivity detector for N_2O analysis; and a flame ionization detector for CH_4 analysis. Gas levels were determined by comparison with triplicate runs of standard gases of known concentration (Scott Specialty Gases, Plumsteadville, PA), and flux rates were then computed from the change in gas concentration over time. It is important to note that all trace gas collection and processing procedures previously described were conducted according to GRACEnet measurement protocols (Parkin and Kaspar, 2006).

Soil water content (m^3 m^{-3}) was measured periodically throughout the course of this experiment using time-domain reflectometry using a Tektronix 1502B cable tester (Tektronix Inc, Beaverton, OR). The soil moisture sensors had 20-cm-long stainless steel rods, with a rod spacing of 3.0 cm. The sensors were installed vertically from the soil surface for a reading depth of 0 to 20 cm. Sensors were placed between rows positioned close to the gas sampling collars. Measurements were converted to volumetric water content values using Topp's equation (Topp et al., 1980).

Each GHG has an established *Global Warming Potential* (GWP), defined as the ratio of radiative forcing from 1 kg of a gas to 1 kg of CO_2 over a specific interval of time. The GWP of CO_2 is 1, whereas the GWP of CH_4 is 25, and that of N_2O is 298 (Forster et al., 2007). In our study, we multiplied the cumulative flux of each gas across the growing season by its appropriate defined ratio; these values were totaled to give seasonal GWP for each individual plot across all treatment combinations.

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The experiment was conducted using a split-plot design with three replicate blocks. Whole-plot treatments (management system) were randomly assigned to half of each block. Split-plot treatments (CO_2 levels) were randomly assigned to one OTC each within each whole plot. There were a total of 12 OTC, with six of these being ambient CO_2 (three for conventional management and three for conservation management) and the other six being elevated CO_2 (three for conventional management and three for conservation management). Data (including GWP) were totaled across the growing season using a basic numerical integration technique (i.e., trapezoidal rule; Leithold, 1976). It is important to note that these calculations were made strictly for overall treatment comparisons and were not intended to generate quantitative numbers of soil GHG losses due to the relatively low sampling frequency (13 sampling dates across 178 days of study). Statistical data analyses were performed using the Mixed Procedure of the Statistical Analysis System (Littell et al., 1996). A significance level of $P \leq 0.05$ was established *a priori*; trends were considered at $0.05 > P \geq 0.10$.

RESULTS

CO_2 Flux

Elevated atmospheric CO_2 (main effect, across both management systems) increased soil CO_2 flux on five sampling dates (Table 1); similar trends were noted on four other dates. Conventional management (main effect, across both CO_2 treatments) had significantly higher soil CO_2 flux only on a single date; two other dates showed similar trends (Table 1). No significant interaction of CO_2 and management was observed.

Soil CO_2 flux from the conventional management system increased in both CO_2 treatments following a tillage event (day of year [DOY] 138; Fig. 1A); this did not occur in the conservation system (Fig. 1B). After this increase, soil CO_2 flux was primarily affected by rainfall in all treatments, increasing after rainfall events and decreasing as soil dried (Fig. 1C). Although soil water content followed rainfall patterns in all treatments, it should be noted that the conservation system had a higher soil water content than did the conventional system (Fig. 1C); soil water content did not differ among the CO_2 treatments (data not shown). Soil CO_2 flux response to elevated CO_2 was more frequent in the conventional management system (significant increases on DOY 131, 180, and 250, with similar trends on DOY 173, 194, 229, and 292) (Fig. 1A) than in the conservation system (significant increase on DOY 173, with similar trends on DOY 131, 180, and 215) (Fig. 1B).

When totaled across the growing season, soil CO_2 flux was significantly higher under elevated (4.39 Mg CO_2-C ha^{-1}) than ambient (3.34 Mg CO_2-C ha^{-1}) atmospheric CO_2 conditions. Similarly, the conventional system (4.19 Mg CO_2-C ha^{-1}) had significantly higher seasonal soil CO_2 flux than did the conservation system (3.53 Mg CO_2-C ha^{-1}).

N_2O Flux

There was no main effect of elevated CO_2 on soil N_2O flux (Table 1). The main effect of management was that the conventional system had significantly higher soil N_2O flux on three dates (Table 1). As with CO_2 flux, there were no significant interactions between CO_2 and management treatments.

Soil N_2O flux was low throughout most of the study period for all treatments (Fig. 2). Although soil N_2O flux increased in association with rain that occurred in late June to mid-July (DOY 180–194) in the conservation system under elevated CO_2 (Fig. 2B), this relatively small increase did not result in significant treatment effects caused by a large variability among samples.

When totaled across the growing season, there were no significant differences in soil N_2O flux for the CO_2 treatment (ambient, 291.4 g N_2O-N ha^{-1}; elevated, 891.2 g N_2O-N ha^{-1}). Similarly, management did not have a significant effect on soil N_2O flux (conventional, 457.6 g N_2O-N ha^{-1}; conservation, 725.0 g N_2O-N ha^{-1}). Although the interaction of CO_2 and management on seasonal N_2O flux was not significant, it is interesting to note that flux in the conservation system was about

TABLE 1. Statistics for CO_2 Concentration, Management System (M), and Their Interaction (C × M) on Soil CO_2, N_2O, and CH_4 Flux for the Sampling Dates in 2007

	Variable†								
	CO_2			N_2O			CH_4		
DOY	CO_2	M	C × M	CO_2	M	C × M	CO_2	M	C × M
115	0.460	0.932	0.653	0.925	0.718	0.682	**0.019**	0.183	0.141
131	**0.010**	0.101	0.324	0.404	0.237	0.218	0.802	0.417	0.630
153	0.666	**<0.001**	0.204	0.411	**0.014**	0.135	0.720	0.642	0.904
173	**0.016**	0.093	0.816	0.221	0.477	0.616	0.960	0.934	0.419
180	**0.006**	0.110	0.203	0.346	0.198	0.094	**0.030**	0.325	0.648
187	0.093	0.655	0.645	0.362	0.340	0.387	0.102	0.306	0.833
194	0.057	0.146	0.593	0.358	0.348	0.330	0.955	0.725	0.361
215	0.171	0.662	0.226	0.597	0.400	0.559	0.523	0.236	0.407
229	0.062	0.087	0.296	0.383	**0.048**	0.694	0.435	0.329	0.359
250	**0.007**	0.250	0.064	0.216	0.395	0.108	0.219	0.381	0.853
264	0.079	0.362	0.750	0.638	**0.014**	0.269	0.493	**0.016**	**0.044**
278	0.682	0.668	0.242	0.643	0.433	0.967	0.518	0.085	0.457
292	**0.049**	0.309	0.744	0.577	0.432	0.210	0.993	0.509	0.340
Total	**0.002**	**0.043**	0.127	0.281	0.617	0.389	0.946	0.224	0.174

Pr > F: statistics. Bold represents significance.

†DOY: day of year; CO_2: carbon dioxide in kg CO_2-C ha^{-1} day^{-1}; N_2O: nitrous oxide in g N_2O-N ha^{-1} day^{-1}; CH_4: methane in g CH_4-C $ha^{-1}day^{-1}$.

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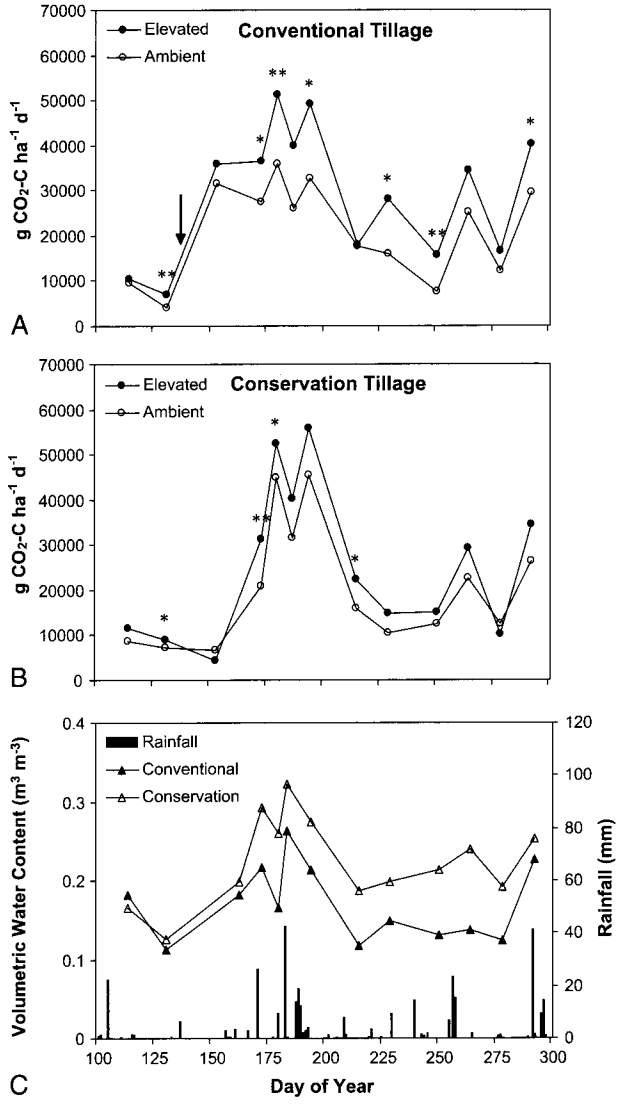

FIG. 1. Flux of CO_2 from a conventional management system (A) and a conservation management system (B) exposed to elevated and ambient levels of atmospheric CO_2 for 10 years. Soil CO_2 flux data were collected during the final growing season in this study. The arrow indicates when tillage occurred (conventional system only). Asterisks represent dates when the CO_2 treatments differed significantly (**$P \leq 0.05$; *$0.05 < P \leq 0.10$). Rainfall (solid bars) and volumetric soil water content (C) are shown for this same sampling period.

half that in the conventional system under ambient CO_2 conditions (392.7 g N_2O-N ha^{-1} day^{-1} and 198.9 g N_2O-N ha^{-1} day^{-1} for conventional and conservation, respectively), whereas the opposite occurred under elevated CO_2 (522.4 g N_2O-N ha^{-1} day^{-1} and 1,260.0 g N_2O-N ha^{-1} day^{-1} for conventional and conservation, respectively).

CH_4 Flux

Elevated atmospheric CO_2 decreased soil CH_4 flux on two sampling dates (Table 1). Conventional management had significantly higher soil CH_4 flux on one date; one other date showed a similar trend (Table 1). A significant interaction of CO_2 and management was observed on DOY 264, in which conventional management had significantly higher soil CH_4 flux only in the elevated CO_2 treatment.

As with N_2O, soil CH_4 flux tended to be low throughout the study (Fig. 3). In general, soil CH_4 flux tended to be less responsive to rainfall than did the other trace gases, although CH_4 flux did tend to decrease during drier periods. An exception to this was noted where CH_4 flux increased after rain late in the growing season on DOY 264, as the treatment interaction previously detailed. It was noted that soil CH_4 flux was sometimes negative; this occurred in all treatment combinations with similar frequency (five or six sampling dates), and treatment differences were rarely significant (as noted for the previously mentioned main effects).

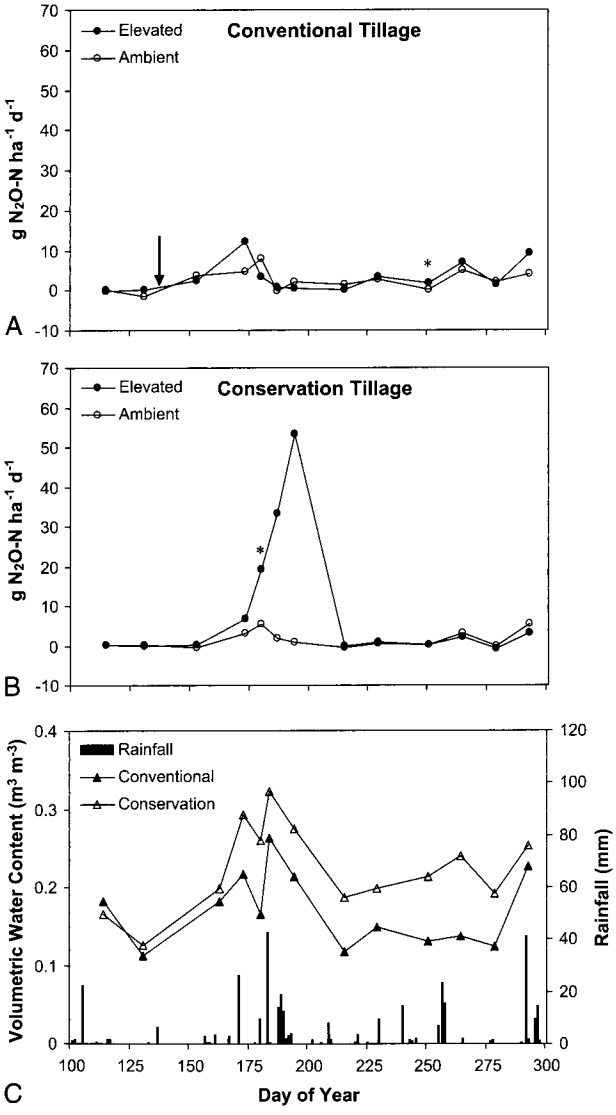

FIG. 2. Flux of N_2O from a conventional management system (A) and a conservation management system (B) exposed to elevated and ambient levels of atmospheric CO_2 for 10 years. Soil N_2O flux data were collected during the final growing season in this study. The arrow indicates when tillage occurred (conventional system only). Asterisks represent dates when the CO_2 treatments differed significantly (**$P \leq 0.05$; *$0.05 < P \leq 0.10$). Rainfall (solid bars) and volumetric soil water content (C) are shown for this same sampling period.

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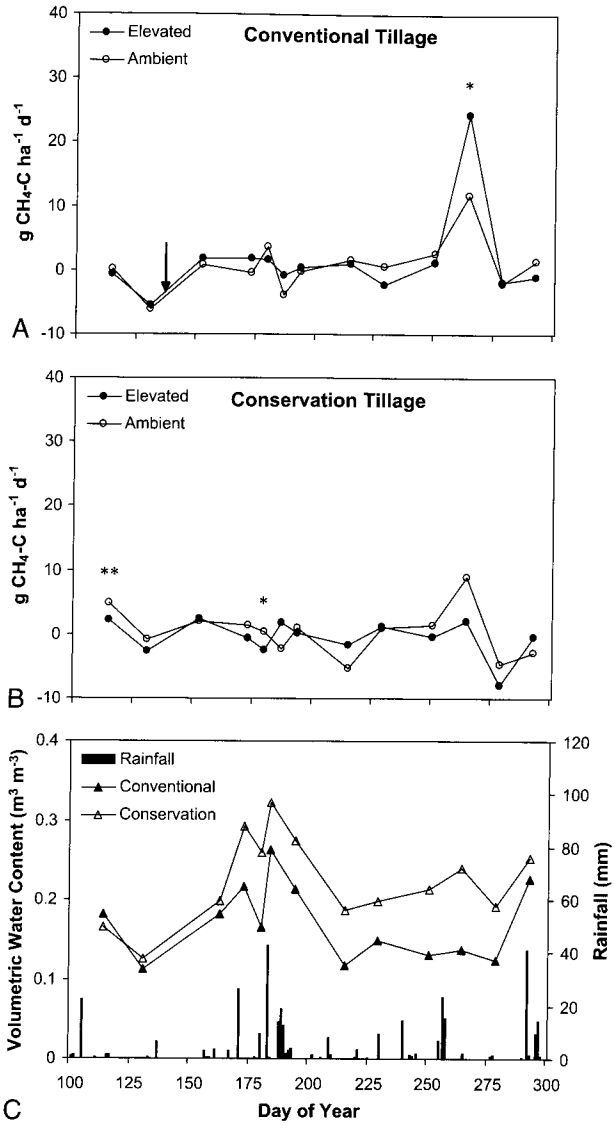

FIG. 3. Flux of CH_4 from a conventional management system (A) and a conservation management system (B) exposed to elevated and ambient levels of atmospheric CO_2 for 10 years. Soil CH_4 flux data were collected during the final growing season in this study. The arrow indicates when tillage occurred (conventional system only). Asterisks represent dates when the CO_2 treatments differed significantly (**$P \leq 0.05$; *$0.05 < P \leq 0.10$). Rainfall (solid bars) and volumetric soil water content (C) are shown for this same sampling period.

When totaled across the growing season, there were no significant differences in soil CH_4 flux for the CO_2 treatment (ambient, 95.0 g CH_4-C ha^{-1}; elevated, 88.3 g CH_4-C ha^{-1}). Similarly, management did not have a significant effect on soil CH_4 flux (conventional, 192.8 g CH_4-C ha^{-1}; conservation, -9.5 g CH_4-C ha^{-1}).

Global Warming Potential

Given that soil N_2O and CH_4 flux were both low throughout the study, GWP was dominated by soil CO_2 flux. In fact, the contribution of soil CO_2 flux to GWP was between 97% and 99% for each of the treatment combinations (data not shown). When totaled across the growing season, GWP was significantly higher ($P = 0.002$) under elevated (16,490.7 CO_2 equivalents ha^{-1}) than ambient (12,358.4 CO_2 equivalents ha^{-1}) atmospheric CO_2 conditions. Similarly, the conventional system (15,563.3 CO_2 equivalents ha^{-1}) tended to have a higher ($P = 0.094$) seasonal GWP than did the conservation system (13,285.8 CO_2 equivalents ha^{-1}). There was no significant interaction ($P = 0.225$) between CO_2 and management treatments.

DISCUSSION

CO_2 Flux

Elevated atmospheric CO_2 in our study increased soil CO_2 flux on several dates and for the seasonal total, with the increase being in the range of 15% to 50% as reported in the literature (Nakayama et al., 1994; Verburg et al., 1998; Zak et al., 2000). Elevated CO_2 can increase soil CO_2 flux in several ways. First, elevated CO_2 increases plant growth, with roots often showing the greatest relative increase among plant organs (Rogers et al., 1994). Greater root biomass can lead to increased autotrophic respiration (Nakayama et al., 1994; Zak et al., 2000). Second, roots of plants grown under elevated CO_2 show increased root exudation (Norby et al., 1987; Lekkerkerk et al., 1990), leading to larger pools of labile C in the rhizosphere (Zak et al., 1993). This increase in easily decomposable C can increase heterotrophic respiration by increasing the size and activity of rhizosphere microbial communities (Goudriaan and de Ruiter, 1983). Third, elevated CO_2 can increase heterotrophic respiration *via* increasing the amount of plant residue on the soil available for microbial decomposition (Torbert et al., 2000). Lastly, elevated CO_2 has been shown to increase plant water use efficiency (Rogers and Dahlman, 1993; Prior et al., 2010). This, in combination with greater surface residue (Prior et al., 2005) reducing evaporative water losses (Reicosky et al., 1999), could increase microbial activity and lead to increased heterotrophic respiration. Therefore, the increased soil CO_2 flux noted here was not unexpected. However, the increase in soil C observed in this study resulting from increased biomass production (Prior et al., 2005; Runion et al., 2009) indicates that the elevated CO_2 treatments are storing soil C despite higher soil CO_2 flux.

In contrast to atmospheric CO_2 treatments, management had little effect on soil CO_2 flux. A major exception was the large increase in soil CO_2 flux after tillage in the conventional system. This has been observed by others and is caused by the immediate release of CO_2 from mechanical (physical) soil disturbance (Prior et al., 1997, 2000, 2004; Reicosky, 1997; Franzluebbers et al., 1998; Morris et al., 2004). Because tillage results in mixing of soil with surface residue, the C substrates are rapidly acted upon by microbes (biological), resulting in further flux of CO_2 to the atmosphere (Franzluebbers et al., 1998; Morris et al., 2004; Prior et al., 2004; Runion et al., 2004). Despite the added biomass from cover crops in the conservation system (and its potential benefit in conserving soil moisture), soil CO_2 flux was not significantly different from that measured in the conventional system on most dates. In fact, the conservation system had a 16% reduction in soil CO_2 flux when totaled across the entire season, most likely resulting from the large loss occurring in the conventional treatment during tillage. This lower CO_2 loss, in conjunction with residue from both row and cover crops not being incorporated in the conservation system, resulted in a significant increase in soil C storage in this system (Prior et al., 2005; Runion et al., 2009).

Our observed increase in soil CO_2 flux following rainfall in both management systems has been reported in many ecosystems (Birch, 1958; Davidson et al., 1993; Reicosky et al., 1999; Franzluebbers et al., 2000; Borken et al., 2003; Austin et al.,

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2004; Huxman et al., 2004; Prior et al., 2004). There are several hypotheses to explain this CO_2 flux, including the following: oxidation of soil organic matter, which becomes available as wetting and drying physically disrupts soil aggregates (Appel, 1998); osmotic shock to the microbial biomass pool releasing organic matter that is used by the remaining microbes (Kieft et al., 1987); liberation of CO_2 bound in soil carbonates (Emmerich, 2003); and rainwater displacing CO_2 that accumulates in soil pore space during dry periods (Huxman et al., 2004).

N_2O Flux

Although soil N_2O flux in this study tended to be low (range, -1.5 to 53.4 g N_2O-N ha^{-1} day^{-1}, with losses equaling 0.4–2.6 kg N_2O-N ha^{-1} $year^{-1}$), values are in the range reported in the literature. For example, Zhijian et al. (2008) reported emissions ranging from 0.7 to 39.4 g N_2O-N ha^{-1} day^{-1} for various crops. In particular, our values align with other studies examining unfertilized crops. Liu et al. (2005) reported N_2O emissions of 1.3 g N_2O-N ha^{-1} day^{-1} in a corn crop receiving no N fertilization, with emissions being an order of magnitude higher in fertilized plots. Kaiser and Ruser (2000) reported emissions ranging from 0.5 to 16.8 kg N_2O-N ha^{-1} $year^{-1}$ for various crops, with emissions from N-fixers being 1.3 to 3.0 kg N_2O-N ha^{-1} $year^{-1}$.

Moisture and N availability have been shown to be the main limiting factors for N_2O production, with C availability also regulating denitrification activity (Groffman, 1999; Kettunen et al., 2006). For example, Jacinthe and Dick (1997) reported seasonal N_2O emissions ranging from 0.6 to 1.2 kg N_2O-N ha^{-1} in a corn/soybean rotation study during a dry year and 1.6 to 3.7 kg N_2O-N ha^{-1} during a subsequent wetter growing season. In our study, rainfall during the sampling period tended to occur frequently (40 events across 178 days of study) but in low amounts (range, 0.03–42.7 mm; average, 1.6 mm; with only 14 of the 40 days having greater than 5 mm) (Fig. 2), suggesting that soil moisture conditions would not, generally, favor N_2O production. Furthermore, soybean (being an N fixer) was grown without the addition of inorganic N fertilizer. Relatively low rainfall with no N addition may have contributed to the low emissions and lack of significant differences in N_2O flux between the two CO_2 treatments.

Tillage has been shown to increase N mineralization and thus gaseous losses of N through soil aeration, soil moisture evaporation, and accessibility of crop residues to soil microbes (Follet and Schimel, 1989; Woods, 1989). Gaseous losses of N have also been observed under no-till because of increased denitrification (Ball et al., 1999). In general, management had little impact on soil N_2O flux in our study. Despite the fact that soil N_2O flux was higher under conventional management on a few dates, these differences were numerically small and did not affect seasonal N_2O loss. Liu et al. (2006) also reported that emissions tended to be slightly higher under conventional tillage (1.2 g N_2O-N ha^{-1} day^{-1}) compared with no-till (0.7 g N_2O-N ha^{-1} day^{-1}) for corn grown without fertilizer additions. A review of the literature (Six et al., 2004) shows that N_2O flux after conversion to no-till can depend greatly on the length of time of adoption of the new practice; that is, after 5 and 10 years, no-till had higher net N_2O flux than conventional systems, but after 20 years, this trend was reversed. They also point out that there remains a high degree of uncertainty around these estimates.

CH_4 Flux

Most of agriculture's contribution of CH_4 flux results from growing rice and from animal production, whereas row crop agriculture tends to contribute little and can sometimes act as a sink (Johnson et al., 2007). Methane flux in our study was highly variable (range, -7.93 to 24.41 g CH_4-C ha^{-1} day^{-1}) and was negative (sink) in about equal samplings as positive (source), although values were most often not different from zero. Others have reported similar high levels of variability in CH_4 flux (Chan and Parkin, 2001a).

Conservation management systems have frequently been shown to act as sinks for CH_4 (Chan and Parkin, 2001b; Berg et al., 2006; Johnson et al., 2007). In our study, the conservation system showed negative flux rates (i.e., sink) on six sample dates, as well as for the seasonal total. Likewise, the conventional system also exhibited negative fluxes on five sample dates. However, CH_4 fluxes (whether positive or negative) generally did not differ from zero. The conventional system had higher CH_4 flux only on one date, and the seasonal totals did not differ between the two management systems. In general, elevated CO_2 tended to have lower soil CH_4 flux, but this difference was significant only on two dates and did not impact the seasonal totals. Similar to the management effects, both CO_2 treatments had negative CH_4 fluxes on about half the sampling dates. Methane is produced under anaerobic conditions (e.g., during rice production), and elevated CO_2 can enhance CH_4 flux in rice systems (Cheng et al., 2001, 2005; Hoque et al., 2001). In contrast to rice, row crop agriculture rarely exists under anaerobic conditions and is, therefore, unlikely to be a major contributor to CH_4 production. Although agricultural soils can act as a sink for CH_4 (Chan and Parkin, 2001b), soil in our study was neither a source nor sink for CH_4, regardless of management or atmospheric CO_2 concentration.

Global Warming Potential

In our study, GWP was driven by the flux of CO_2. This is supported by the fact that there were no significant season-long differences in N_2O or CH_4 flux. This contention is also supported by the fact that soil CO_2 flux accounted for 97% to 99% of GWP across all treatment combinations. Our results indicate that elevated atmospheric CO_2 increased GWP. In addition, conventional management tended to have higher GWP than did the conservation system, with the bulk of this increase related to soil CO_2 flux during the tillage event. These results are consistent with previous reports (Johnson et al., 2007; Berg et al., 2006; Chan and Parkin, 2001b), which show that the GWP in conservation systems is lower than in conventional systems.

CONCLUSIONS

The objective of this study was to evaluate soil flux of GHG (CO_2, N_2O, and CH_4) from conservation and conventional management systems that had been under the influence of elevated atmospheric CO_2 for 10 years. Although data were collected only on 13 sampling dates in the final year of study (and these values are not intended to represent total actual soil GHG flux), this study is the first to show the qualitative effects of agricultural management under current (ambient) and future (elevated) atmospheric CO_2 conditions on soil trace gas flux. Elevated atmospheric CO_2 and conventional management increased soil CO_2 flux. Flux of both N_2O and CH_4 remained low throughout most of the growing season and rarely showed differences caused by atmospheric CO_2 level or land management (conventional vs. conservation). Although infrequent differences in flux of CH_4 and N_2O were observed, the seasonal GWP of these gases was not significantly affected by either treatment. In our study, GWP was increased by both elevated CO_2 and conventional management, and this increase was caused by increased soil CO_2 flux. It has been suggested (Li et al., 2005) that land management (e.g., conservation vs. conventional) will

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become an increasingly important issue because of its impact on fluxes of GHG, and these effects may become more pronounced as atmospheric CO_2 continues to rise. Our results indicate that conversion to conservation management may reduce agriculture's potential contribution to global climate change.

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