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Impact of Tillage and Fertilizer Application Method on Gas Emissions in a Corn Cropping System*[1]

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ABSTRACT

Tillage and fertilization practices used in row crop production are thought to alter greenhouse gas emissions from soil. This study was conducted to determine the impact of fertilizer sources, land management practices, and fertilizer placement methods on greenhouse gas (CO_2, CH_4, and N_2O) emissions. A new prototype implement developed for applying poultry litter in subsurface bands in the soil was used in this study. The field site was located at the Sand Mountain Research and Extension Center in the Appalachian Plateau region of northeast Alabama, USA, on a Hartsells fine sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludults). Measurements of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions followed GRACEnet (greenhouse gas reduction through agricultural carbon enhancement network) protocols to assess the effects of different tillage (conventional *vs.* no-tillage) and fertilizer placement (subsurface banding *vs.* surface application) practices in a corn (*Zea mays* L.) cropping system. Fertilizer sources were urea-ammonium nitrate (UAN), ammonium nitrate (AN) and poultry litter (M) applied at a rate of 170 kg ha^{-1} of available N. Banding of fertilizer resulted in the greatest concentration of gaseous loss (CO_2 and N_2O) compared to surface applications of fertilizer. Fertilizer banding increased CO_2 and N_2O loss on various sampling days throughout the season with poultry litter banding emitting more gas than UAN banding. Conventional tillage practices also resulted in a higher concentration of CO_2 and N_2O loss when evaluating tillage by sampling day. Throughout the course of this study, CH_4 flux was not affected by tillage, fertilizer source, or fertilizer placement method. These results suggest that poultry litter use and banding practices have the potential to increase greenhouse gas emissions.

Key Words: conventional tillage, global warming potential, greenhouse gases, no-tillage, poultry litter

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INTRODUCTION

Poultry production in the USA generates approximately 11.4 million tonnes of poultry litter (a mixture of manure and bedding material) annually (USDA National Agricultural Statistics Service, 2007). Over the past two decades, poultry production in the USA has experienced substantial growth, resulting in large amounts of manure/litter that must be disposed. This poultry litter has to be disposed in an environmentally sound way. Historically, the most common disposal practices have been land application to pastures. Land application for sustainable row crop production may serve as a means of disposal for the increasing supply of litter. The traditional method of land-applying poultry litter is broadcast application on the soil surface but this leaves the nutrients, solids, and other constituents in the litter vulnerable to being transported from the field in runoff water, into streams, rivers, lakes, and other water bodies (Sharpley, 1995). Also, land application of manure can contribute significant amounts of greenhouse gases to the atmosphere. A new prototype implement for applying poultry litter in subsurface bands in the soil has been developed by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) in Auburn, Alabama (Farm Show Publishing, Inc., 2009). The implement applies poultry litter in pastures, and in a side-dressing fashion to row crops. Thus, management practices need to be identified to better utilize manure nutrients, while at the same time safeguarding the environment. Considerable effort has been made to develop new technology that minimizes nutrient and gaseous losses. The prototype implement for subsurface band

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application of poultry litter may reduce emissions of greenhouse gases to the atmosphere. Therefore, information is needed on the impact of surface application *vs.* subsurface banding of poultry litter on crop production and environmental quality.

Greenhouse gases naturally keep the earth warm by trapping heat in the atmosphere, thus increases in atmospheric concentrations of these gases are predicted to shift the earth's climate. The concentration of carbon dioxide (CO_2) in the atmosphere is increasing at an unprecedented rate, due primarily to fossil fuel burning and land use change. The increased awareness of this global problem has led to increased pressure by society to minimize the impacts of elevated atmospheric concentrations of greenhouse gases. Methane (CH_4) and nitrous oxide (N_2O), in addition to CO_2, are important greenhouse gases contributing to global climate change. Each greenhouse gas has a specific 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; *i.e.*, the GWP of CO_2 is 1, while the GWP of CH_4 is 21, and that of N_2O is 310 (Lal *et al.*, 1998). Animal and crop production may account for as much as 70% of the annual global anthropogenic N_2O emitted and about 33% of global CH_4, with these agricultural emissions projected to increase in the future (Mosier *et al.*, 1998; Mosier, 2001). Given the potential of these greenhouse gases to contribute to global climate change, impacts of management and environmental factors on their efflux from soil have begun to receive more focused attention. Agriculture and other land uses have been shown to act as sources and sinks of these three important greenhouse gases (Mosier *et al.*, 1998; Mosier, 2001). Because of this and their impact on global climate, a need exists to evaluate fluxes of these gases under different land use and soil management practices.

Kessavalou *et al.* (1998) found that CH_4 and N_2O flux from agricultural soil increased following tillage events; they suggested that no-tillage systems represented the least threat to deterioration of both the atmosphere and soil quality. Li and Butterbach-Bahl (2005) observed in a 20 year study that reduced tillage enhanced crop residue retention and farmyard manure application increased C sequestration while increasing N_2O emissions, but had little impact on CH_4 emissions. Over this 20 year period, increased N_2O emissions from reduced tillage and farmyard manure offset C storage 75%–310% depending on the tillage and fertilizer source evaluated. Some of the land management practices that stored soil C had higher N_2O emissions and this resulted in those practices being overall sources for global warming gases as opposed to reducing greenhouse gas emissions (Li and Butterbach-Bahl, 2005). Venterea *et al.* (2005) reported that emissions of N_2O were higher in a no-tillage system compared to conventional tillage when using broadcast applied urea. Higher CH_4 soil absorbance rates and lower gas emissions were observed under reduced tillage practices compared to conventional tillage methods in areas receiving UAN and broadcasted urea (Venterea *et al.*, 2005). Chan and Parkin (2001b) found that agricultural sites tended to be net producers of CH_4, while natural systems (prairie or forest) tended to be net consumers; this disparity was related to differences in microbial populations (mainly CH_4 oxidizers) (Chan and Parkin, 2001a). Parkin and Kaspar (2006) found no differences in N_2O emissions between different management systems (tillage or cover crops) in a corn-soybean rotation.

Anhydrous NH_3 and NH_4NO_3 have been commonly used as nitrogen (N) sources; however, applications of anhydrous NH_3 can be dangerous and requires equipment that is expensive relative to granular fertilizer equipment. Further, new regulations on the purchase of NH_4NO_3 have caused farmers to use alternative N sources such as urea or urea-ammonium nitrate (UAN). Urea and UAN are more volatile than NH_4NO_3, thus more likely to increase greenhouse gas emissions if not applied properly (McTaggart *et al.*, 2002). Previous research has also shown that gas emissions can be dramatically influenced by fertilizer application methods and tillage practices (Schlesinger and Hartley, 1992; Prior *et al.*, 2004). Thus, better application methods are needed in order to mitigate greenhouse gas emissions from agricultural practices and prevent being a detriment to the environment.

There is a scarcity of research relating the interaction of fertilizer sources, land management practices, and fertilizer placement methods on greenhouse gas emissions. This is especially true for the application of fertilizer in bands, especially application of poultry litter in bands. The objective of the current study was to evaluate the emissions of greenhouse gases (CO_2, CH_4, and N_2O) from a corn system using various tillage systems, fertilizer sources, and fertilizer placement.

MATERIALS AND METHODS

Site description

This field study was conducted during 2007 at the Sand Mountain Research and Extension Center in the Appalachian Plateau region of northeast Alabama, on a Hartsells fine sandy loam (fine-loamy, siliceous, subactive, thermic Typic Hapludults). This soil type consists of moderately deep, well drained moderately permeable soil that was formed from acid sandstone. The study area elevation is 330 m above mean sea level, and average annual precipitation and temperature were 1 370 mm and 17 °C, respectively. In most years, precipitation occurring mainly as rainfall is unevenly distributed and primarily occurs from midwinter to early spring. The surface soil (0–15 cm) at the initiation of the study was characterized as 11.9% clay, 28.6% silt, and 59.6% sand with an average bulk density of 1.5 g cm^{-3}. Soil characteristics were performed by the Auburn University Soil Testing Laboratory (Auburn, Alabama). Previous management of the study site was continuous no-tillage management for at least four years. No-tillage corn (*Zea mays* L.) was grown in 2003–2004 and NT soybean (*Glycine max* L.) was grown in 2005–2006.

Cultural practices and treatments

The experimental design was a randomized complete block with a split plot restriction on randomization in four replicates. Plot size was 7.32 m wide and 7.62 m long, resulting in eight rows of corn. The two tillage treatments investigated consisted of conventional tillage (CT; disking 15 cm, moldboard plowing 30 cm, disking 15 cm followed by rototilling 7 cm in the spring) and no-tillage (NT; planting into crop residue with a double disk-opener planter) as the main plots. Tillage treatments were performed in the spring, occurring approximately 4–5 days before planting. Fertilization treatments (subplots) consisted of poultry litter (M) broadcast surface applied (MS) and subsurface banded (MB), UAN (one-half urea and the other half ammonium nitrate) broadcast surface applied (UANS) and subsurface banded (UANB), AN (ammonium nitrate) broadcast surface applied, and a control (nonfertilized check). The poultry litter and inorganic fertilizers were applied at a rate 170 kg ha^{-1} of available N. For inorganic fertilizer, 100% of the N is assumed to be immediately available. The poultry litter was applied at a rate of 310 kg N ha^{-1} based on 55% of the total N being available the first year after application (Eghball *et al.*, 2002). The cropping system was continuous corn seeded at a rate of 59 300 seed ha^{-1} in 0.914-m rows using a John Deere 7 100 four row NT planter (John Deere Corp, Moline, IL). The corn variety was Croplan 751 Roundup Ready. Other management practices such as lime, P and K, herbicides, and pesticides were applied according to Alabama Agricultural Experiment Station recommendations. Weed control consisted of a pre-emergence broadcast application of atrazine (4.7 L ha^{-1}), metolachlor (3.5 L ha^{-1}), and Gramoxone (4.7 L ha^{-1}). Post emergence herbicide consisted of Roundup applied at a rate of 2.3 L ha^{-1}.

Fertilization occurred two weeks after planting (April 9, 2007). Surface application of fertilizer was performed by broadcasting the fertilizer by hand. Granular urea-ammonium nitrate was subsurface applied alongside each corn row in a side-dressing application approximately 15 cm to the side of corn row, using a subsurface banding applicator implement. The UAN was placed in trenches approximately 4 to 8 cm beneath the soil surface. Poultry litter was applied in the subsurface bands using a prototype subsurface band applicator implement developed at the USDA-ARS National Soil Dynamics Laboratory (Auburn, Alabama). This is a four-row implement designed for applying poultry litter in shallow subsurface bands. The litter was applied alongside each corn row in a side-dressing application and each band was approximately 15 cm to the side of corn row. For each band, the implement formed a trench in the soil, applied litter in the trench, and used its presswheels to backfill soil on top of the litter. Each litter band extended from about 4 to 8 cm beneath the soil surface, so the litter band was covered with about 4 cm of soil. The width of each band was 4 cm. Uncomposted poultry litter used in this study was collected from a local broiler production facility and consisted of a mixture of poultry manure and pine shavings bedding material (Table I).

Gas sampling

Samples of gas emitted from the soil surface were taken with *in situ* custom-made vented static gas flux chambers constructed according to the GRACEnet protocol (Hutchinson and Mosier, 1981; Hutchinson and Livingston, 1993). Base rings were placed in the ground directly after fertilization and remained in the field until after harvest. Flux chambers were installed in the CT and NT systems in the inter-row areas. For

TABLE I

Some nutrient and moisture characteristics of the poultry litter used in this study (on a dry-weight basis)

N	C	P	K	Ca	Mg	Cu	Fe	Mn	Zn	B	Co	Al	Moisture
g kg^{-1}						mg kg^{-1}							g kg^{-1}
26.9	202.2	47.5	28.8	34.8	6.9	53	1804	517	440	55.5	334	2 275	223.5

the two band-applied treatments (MB and UANB), the base ring was positioned so a diameter of the ring was collinear with the centerline of the band, *i.e.*, midway between the left and right edges of the band. Gas samples were taken at 0, 15, 30, and 45 min intervals following chamber closure. This allowed a gas flux rate to be calculated from the change in concentration for the 45 min interval. Gas flux measurements were taken at approximately the same time (midday) each day. At each time interval, gas samples (10 mL) were collected with polypropylene syringes and injected into evacuated glass vials (6 mL) fitted with butyl rubber stoppers as described by Parkin and Kaspar (2006). Flux measurements were taken on the day of fertilization (within one hour after fertilizer application), on each of the first 5 days following fertilization, 2 and 3 weeks after fertilization, and 1, 2, and 3 months after fertilization. Sampling frequency is similar to sampling frequencies used by other investigators (Verchot *et al.*, 2008; Omonode *et al.*, 2007; Oorts *et al.*, 2007) with intensive sampling concentrated around times when high fluxes are expected. Greenhouse gas fluxes typically have high variability during the first week following fertilization. For this reason, we sampled daily for the first 6 days of the experiment. Samples were stored at 25 °C until analyzed. Soil moisture was measured in the top 5 cm at time of gas sampling using a portable soil moisture meter (Th_2O probe, Dynamax Inc., Houston, Texas). Soil temperature was also measured at sampling in the top 10 cm of the soil profile using a digital thermometer probe (Traceable Digital Thermometer, Fisher Scientific, Pittsburgh, Pennsylvania).

Concentrations of CO_2, CH_4, and N_2O were determined by comparison to a standard curve using standards obtained from Scott Specialty Gases (Plumsteadville, Pennsylvania). Gas flux rates were determined using the linear or curvilinear equations as appropriate as directed by the GRACEnet protocol (Parkin and Kaspar, 2006). Gas samples were analyzed by a gas chromatograph (Shimadzu GC-2014, Columbia, Maryland) equipped with three detectors: thermal conductivity detector for CO_2; electron capture detector for N_2O; and flame ionization detector for CH_4. The minimum detectable concentration change was ± 10.2 µmol m^{-2} min^{-1} for CO_2, 0.06 µmol m^{-2} min^{-1} for CH_4, and 0.07 µmol m^{-2} min^{-1} for N_2O.

Band flux determination

Within each chamber that was centered over a subsurface band, a portion of the soil surface was directly above the subsurface band and the remainder of the soil surface was the non-banded area within the chamber. The ratio of this band area to the non-banded area within the chamber was considerably greater than the ratio of band area to non-banded area for a complete plot that received a subsurface band treatment. Thus, for each of the subsurface banded plots, the effective gas flux for the plot, which is the flux of a gas emitted by the complete plot, was calculated. The flux from a subsurface band alone was calculated, and then the effective gas flux for the subsurface banded plot was calculated as the weighted average of the flux from the subsurface band and the flux from the control area that received no fertilizer or manure (Way *et al.*, 2011).

Data analysis

The tillage treatments (NT and CT) were the main plots with fertilization as the split plots. Statistical analyses of data were performed using the PROC GLM procedure of SAS (SAS Institute Inc., 1999). Normality and equal variance assumptions were checked by PROC UNIVARIATE and by graphing the residuals. When warranted and transformation was appropriate, the correct transformation was applied as by PROC TRANSREG. Transformed data were utilized for statistical analysis, but all means shown in tables and figures are reported as untransformed data. Carbon dioxide and N_2O flux data were log transformed and CH_4 flux data were square root transformed. Interactions of main effects were tested; main effects were tillage and fertilizer treatment. These interactions were checked and found not to be significant for greenhouse gases; so only statistical results for main effects are reported. The banded *vs.* the surface applied treatments were evaluated using the UAN broadcast surface applied, UAN subsurface banded, manure broadcast surface applied and manure subsurface banded treatments only. Mean separations for all data were performed using LSD at $P < 0.05$ probability level. When averages are reported, they are arithmetic averages. Carbon dioxide equivalents were calculated for each gas on each chamber for each date sampled using the previously published global warming potential values for each greenhouse gas and treated as an additional response variable and analyzed in a similar fashion to the greenhouse gas flux data (Lal *et al.*, 1998).

RESULTS

Carbon dioxide flux

Carbon dioxide fluxes were significantly higher in the CT treatment compared to the NT treatment on April 16, June 4, and July 12 (Fig. 1a). These signifi-

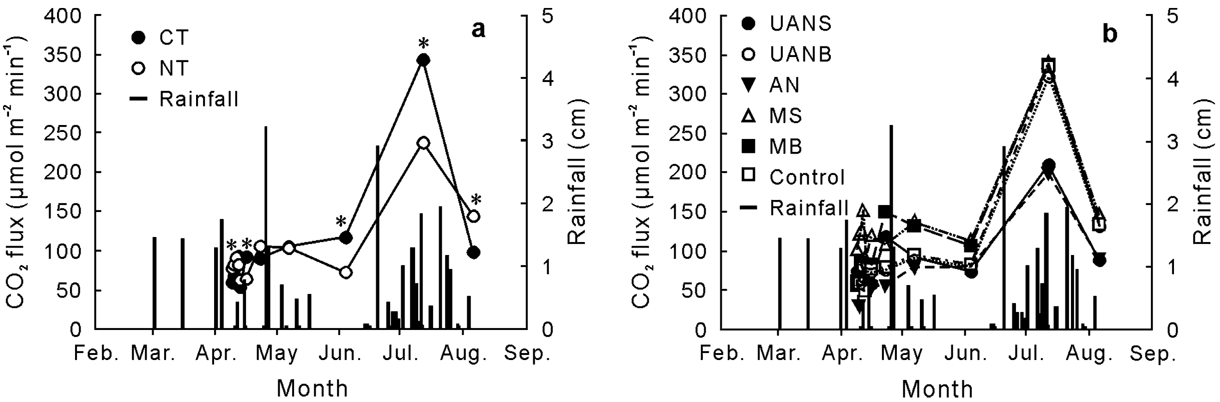

Fig. 1 Efflux of CO_2 (a) from conventional tillage (CT) and no-tillage (NT) systems for 11 sampling days and (b) from AN (ammonium nitrate), MB (poultry litter subsurface banded), MS (poultry litter broadcast surface applied), UANB (urea-ammonium nitrate subsurface banded), UANS (urea-ammonium nitrate broadcast surface applied), and control (non-fertilized check) systems. An asterisk (∗) indicates significant differences at $P = 0.05$ on a particular date between tillage plots; and information about significant differences for fertilizer treatments can be found in Table II.

TABLE II

Mean fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from conventional tillage (CT) and no-tillage (NT) plots under fertilizer treatments of ammonium nitrate (AN), poultry litter subsurface banded (MB), poultry litter broadcast surface applied (MS), urea-ammonium nitrate subsurface banded (UANB), urea-ammonium nitrate broadcast surface applied (UANS), and control (non-fertilized check)

Fertilizer treatment	CO_2			CH_4			N_2O		
	NT	CT	Average	NT	CT	Average	NT	CT	Average
	µmol m^{-2} min^{-1}								
AN	64.16	92.20	78.18c[a)]	0.00	−0.01	0.00a	0.01	0.01	0.01b
MB	112.19	122.61	117.40ab	−0.01	0.00	−0.01a	0.06	0.09	0.08a
MS	154.09	127.19	140.64a	0.00	−0.02	−0.01a	0.02	0.01	0.02b
UANB	97.19	105.44	101.31bc	−0.01	0.00	0.00a	0.01	0.02	0.01b
UANS	84.14	100.40	92.27bc	0.00	−0.02	−0.01a	0.01	0.01	0.01b
Control	99.82	105.52	102.67bc	−0.01	0.00	0.00a	0.00	0.00	0.00b
Average	101.93a[b)]	108.89a		−0.01a	−0.01a		0.02a	0.02a	

a)Means followed by the same letter(s), within each column, are not significantly different at $P < 0.05$.
b)In the last row, means followed by the same letter, within each pair of columns, are not significantly different at $P < 0.05$.

cant differences were large (on the order of 40–100 µmol m^{-2} min^{-1}) on all three dates; however, the average CO_2 flux across the entire growing season did not show significant differences in CO_2 flux between the CT treatment and NT treatment (Table II). In addition, the NT treatment showed significantly higher CO_2 fluxes on two dates (April 9; August 6); however, these differences were relatively small.

In addition to tillage, fertilizer source also significantly impacted soil CO_2 flux (Fig. 1b). The poultry litter surface applied (MS) treatment had significantly higher CO_2 flux on all sampling dates and was the highest overall emitter of CO_2 in both the CT and NT treatments (Tables II and III). The highest CO_2 fluxes were in the warmest parts of the season (*i.e.*, May 7, June 4 and July 12; Fig. 1, Table IV).

In addition to tillage and fertilizer source, fertilizer placement significantly impacted soil CO_2 flux on a few sampling dates; however, the average seasonal flux did not show any significant differences (Table V).

Methane flux

Methane fluxes remained low relative to the other greenhouse gases throughout the sampling season. Methane flux was not significantly impacted by tillage on any sampling date (Tables II, III and V; Fig. 2). However, one sampling date did show significant differences in soil methane flux with different fertilizer sources and placement. On April 13, the control had significantly higher flux than the UANS and the banded treatments had significantly higher flux than the surface applied treatments at the $P < 0.05$ level (Tables II, III and V; Fig. 2).

Nitrous oxide flux

Nitrous oxide fluxes were low throughout the growing season; however, significant differences were observed between tillage plots, fertilizer source, and ferti-

TABLE III

Statistical analysis of mean daily gas flux for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) averaged over tillage plots under fertilizer treatments of ammonium nitrate (AN), poultry litter subsurface banded (MB), poultry litter broadcast surface applied (MS), urea-ammonium nitrate subsurface banded (UANB), urea-ammonium nitrate broadcast surface applied (UANS), and control (non-fertilized check)

Gas	Fertilizer Treatment	April 9	April 10	April 11	April 12	April 13	April 16	April 23	May 7	June 4	July 12	August 6
CO_2	AN	ab[a)]	b	b	b	b	b	a	a	c	b	a
	MB	ab	b	b	b	ab	ab	a	a	ab	a	a
	MS	a	a	a	a	a	a	a	a	a	a	a
	UANB	ab	ab	ab	b	b	ab	a	a	abc	a	a
	UANS	ab	ab	ab	b	b	b	a	a	c	b	a
	Control	b	b	b	b	b	ab	a	a	abc	a	a
N_2O	AN	ab	b	b	ab	b	a	b	b	b	b	a
	MB	b	b	b	b	ab	a	a	a	a	a	a
	MS	ab	a	a	a	a	a	b	b	b	b	a
	UANB	b	b	b	b	b	a	b	a	b	ab	a
	UANS	a	b	b	b	b	a	b	b	b	b	a
	Control	b	b	b	b	b	a	b	b	b	b	a
CH_4	AN	a	a	a	a	ab	a	a	a	a	a	a
	MB	a	a	a	a	ab	a	a	a	a	a	a
	MS	a	a	a	a	ab	a	a	a	a	a	a
	UANB	a	a	a	a	ab	a	a	a	a	a	a
	UANS	a	a	a	a	b	a	a	a	a	a	a
	Control	a	a	a	a	a	a	a	a	a	a	a

[a)] For each gas, different letter(s), within each column, indicate significant differences at $P < 0.05$ between fertilizer treatments, averaged across tillage plots.

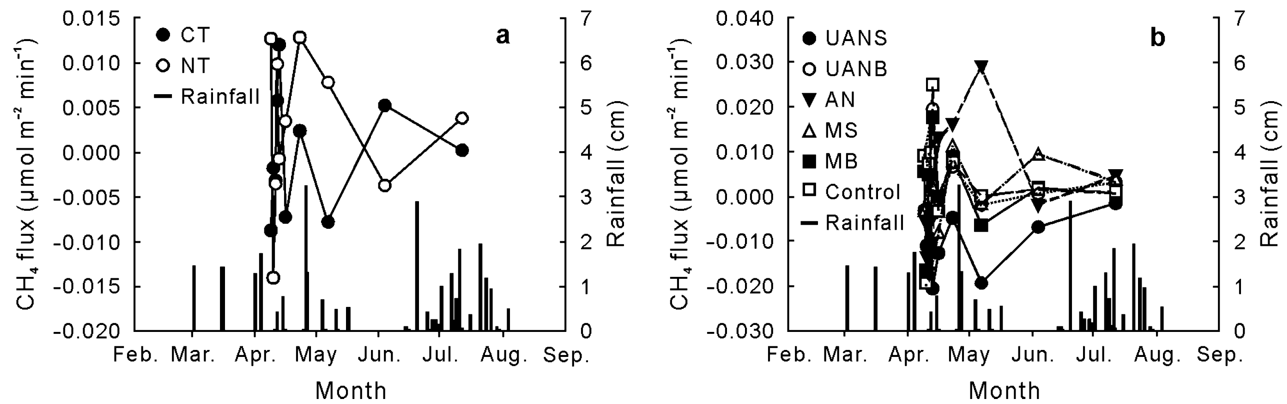

Fig. 2 Efflux of CH_4 (a) from conventional tillage (CT) and no-tillage (NT) systems for 11 sampling days and (b) from AN (ammonium nitrate), MB (poultry litter subsurface banded), MS (poultry litter broadcast surface applied), UANB (urea-ammonium nitrate subsurface banded), UANS (urea-ammonium nitrate broadcast surface applied), and control (non-fertilized check) systems.

lizer placement. One sampling date (June 4) indicated a significantly higher N_2O flux in the CT than in the NT; however, the average N_2O flux for the season did not indicate any difference between the CT and NT (Table II, Fig. 3a).

Fertilizer source significantly impacted N_2O flux. Overall, using poultry litter as a source of fertilizer resulted in significantly higher N_2O flux compared to the other N sources (Table II, Fig. 3b). The average flux of N_2O for treatments fertilized with poultry litter was 0.03 µmol m^{-2} min^{-1}, which is significantly higher than the average flux from UAN (0.01 µmol m^{-2} min^{-1}), AN (0.01 µmol m^{-2} min^{-1}), and the unfertilized control (0.01 µmol m^{-2} min^{-1}). This trend was apparent on several dates throughout the growing season (*i.e.*, April 10, April 11, April 13, April 16, April 23, May 7; Fig. 3b, Table III).

In addition to fertilizer source, fertilizer placement also significantly impacted N_2O flux rates. Overall, the banded treatments had significantly higher flux than the surface applied and control treatments (Table V). This trend was apparent on several sampling dates (April 23, May 5, June 6, July 12 and August 16). However, the opposite trend (*i.e.*, surface applied

TABLE IV

Mean daily soil temperature (ST) and moisture content (SM) for the 11 gas flux sampling dates in 2007 and the fertilizer treatments of ammonium nitrate (AN), poultry litter subsurface banded (MB), poultry litter broadcast surface applied (MS), urea-ammonium nitrate subsurface banded (UANB), urea-ammonium nitrate broadcast surface applied (UANS), and control (non-fertilized check)

Sampling date	Temperature or moisture	Conventional tillage (CT)							No-tillage (NT)						
		AN	MB	MS	UANB	UANS	Control	Average	AN	MB	MS	UANB	UANS	Control	Average
April 9	ST (°C)	11.4abc[a]	11.5ab	9.5fg	10.0defg	9.8gef	9.3g	10.2B[b]	12.1a	12.2a	10.5cd	10.8bcd	10.6bcde	10.4def	11.1A
	SM (cm^3 cm^{-3})	0.119cd	0.109cd	0.092d	0.147bc	0.097d	0.091d	0.109B	0.191a	0.200a	0.194a	0.180ab	0.184ab	0.189ab	0.189A
April 10	ST (°C)	11.3a	11.2a	11.2a	11.3a	11.5a	11.3a	11.3A	11.8a	11.6a	11.8a	11.5a	11.6a	11.7a	11.7A
	SM (cm^3 cm^{-3})	0.118b	0.122b	0.099b	0.126b	0.104b	0.120b	0.115B	0.177a	0.192a	0.184a	0.178a	0.188a	0.193a	0.185A
April 11	ST (°C)	12.0a	12.01a	12.3a	12.0a	12.1a	11.9a	12.1A	12.4a	12.4a	12.3a	12.2a	12.3a	11.7a	12.2A
	SM (cm^3 cm^{-3})	0.177ab	0.157b	0.173ab	0.168ab	0.178ab	0.163b	0.169B	0.223a	0.203ab	0.215ab	0.208ab	0.195ab	0.207ab	0.209A
April 12	ST (°C)	11.7a	11.8a	11.7a	11.6a	11.7a	11.6a	11.7A	11.9a	12.0a	12.0a	12.0a	11.9a	11.9a	12.0A
	SM (cm^3 cm^{-3})	0.161bcd	0.149cd	0.154bcd	0.150cd	0.143d	0.144d	0.150B	0.213a	0.193abc	0.199ab	0.198ab	0.211a	0.192abc	0.201A
April 13	ST (°C)	11.9a	12.1a	12.3a	12.0a	12.18a	11.8a	12.0A	12.3a	12.2a	12.3a	12.2a	12.3a	12.3a	12.3A
	SM (cm^3 cm^{-3})	0.142bcd	0.130cd	0.132ce	0.151bcd	0.129d	0.129cd	0.136B	0.194a	0.172ab	0.198a	0.175ab	190.7a	160.7abc	180.4A
April 16	ST (°C)	9.7a	9.9a	9.8a	9.8a	9.7a	9.5a	9.7A	10.1a	10.1a	10.2a	10.1a	10.1a	10.1a	10.1A
	SM (cm^3 cm^{-3})	0.196ab	0.170b	0.186ab	0.180ab	0.169b	0.163b	0.177B	0.220ab	0.213ab	0.217ab	0.214ab	0.237a	0.206ab	0.218A
April 23	ST (°C)	19.1a	-	-	18.7a	19.5a	18.7a	19.0A	17.6a	17.1a	17.2a	17.4a	17.2a	17.5a	17.4B
	SM (cm^3 cm^{-3})	0.102a	-	-	0.109a	0.092a	0.109b	0.103A	0.149a	0.128a	0.137a	0.109a	0.159a	0.116a	0.132A
June 4	ST (°C)	28.0a	27.5a	27.7a	28.2a	18.2a	28.1a	27.9A	27.8a	27.3a	27.3a	27.5a	27.4a	27.4a	27.4A
	SM (cm^3 cm^{-3})	0.065a	0.035a	0.021a	0.044a	0.047a	0.034a	0.041B	0.063a	0.043a	0.063a	0.063a	0.069a	0.052a	0.059A
July 12	ST (°C)	29.1a	28.8a	32.7a	31.4a	30.1a	29.9a	30.8A	31.8a	30.2a	32.7a	30.4a	30.4a	32.2a	30.3A
	SM (cm^3 cm^{-3})	0.146a	0.150a	0.155a	0.156a	0.148a	0.145a	0.150B	0.163a	0.165a	0.167a	0.156a	0.183a	0.166a	0.168A
August 6	ST (°C)	33.4a	32.6a	32.7a	32.4a	32.5a	32.9a	32.8A	32.8a	34.2a	33.8a	33.5a	33.1a	25.8a	32.2A
	SM (cm^3 cm^{-3})	0.039a	0.049a	0.041a	0.048a	0.051a	0.050a	0.044A	0.045a	0.049a	0.060a	0.039a	0.040a	0.135a	0.061A

[a] Within conventional tillage and within no-tillage, means followed by the same lowercase letter(s), within each row, are not significantly different at $P < 0.05$.

[b] The average values (in the "Average" column) for the soil temperature (ST) and moisture content (SM) followed by the same uppercase letter, within each row (*i.e.*, for a particular date), are not significantly different at $P < 0.05$ between CT and NT.

TABLE V

Statistical analysis of mean daily gas flux for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) averaged over tillage plots and fertilizer treatments

Date	CO_2		N_2O		CH_4	
	Banded	Surface applied	Banded	Surface applied	Banded	Surface applied
	μmol m^{-2} min^{-1}					
April 9	60.6a[a)]	78.5a	0.0036b	0.0089a	0.0070a	−0.0040a
April 10	64.2a	86.3a	0.0039b	0.0089a	−0.0168a	−0.0140a
April 11	83.7a	92.1a	0.0063a	0.0078a	0.0062a	−0.0132a
April 12	76.7a	98.0a	0.0061b	0.0151a	0.0080a	0.0071a
April 13	54.9a	64.4a	0.0096b	0.0130a	0.0187a	−0.0095b
April 16	78.8a	77.6a	0.0238a	0.0259a	−0.0003a	−0.0025a
April 23	113.2a	93.9b	0.0933a	0.0145b	0.0076a	0.0076a
May 7	111.8a	103.0a	0.1009a	0.0229b	−0.0041a	0.0027a
June 4	94.7a	88.6a	0.2229a	0.0033b	0.0014a	0.0003a
July 12	330.1a	249.7b	0.0341a	0.0156b	0.0020a	0.0024a
August 6	134.3a	108.6a	−0.0070a	−0.0024ab	−0.0870a	−0.0670a
Overall	109.4a	103.7a	0.0450a	0.0120b	−0.0050a	−0.0081a

[a)]Means followed by the same letter(s), within each row and for each gas, are not significantly different at $P < 0.05$.

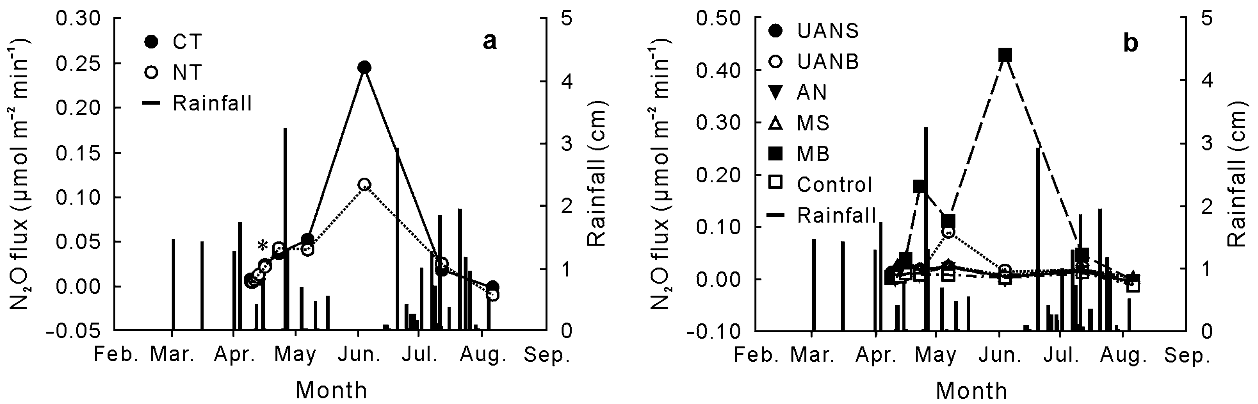

Fig. 3 Efflux of N_2O (a) from conventional tillage (CT) and no-tillage (NT) systems for 11 sampling days and (b) from AN (ammonium nitrate), MB (poultry litter subsurface banded), MS (poultry litter broadcast surface applied), UANB (urea-ammonium nitrate subsurface banded), UANS (urea-ammonium nitrate broadcast surface applied), and control (non-fertilized check) systems. An asterisk (∗) indicates significant differences at $P = 0.05$ on a particular date between tillage plots; and information about significant differences for fertilizer treatments can be found in Table II.

treatments having higher flux than banded treatments) was observed during the early sampling days (April 9, April 10, April 12, and April 13) (Table V). Only the banded treatment was significantly higher than the other two (control and surface applied) when averaged across the entire growing season indicating that surface applications of fertilizers did not significantly increase N_2O flux.

CO_2 equivalents

The CO_2 equivalents were calculated using the flux data from the CO_2, CH_4, and N_2O. This was done by multiplying the flux of CO_2 by 1; CH_4 by 21 and N_2O by 310 (Lal *et al.*, 1998) and summing these numbers together to get CO_2 equivalents as impacted by these three gases in order to compare the overall impact of the gas fluxes in a 100 year time frame. When looking across the entire sampling season there were no significant differences ($P < 0.05$) in CO_2 equivalent between CT and NT systems.

A trend of differences in CO_2 equivalents were found for fertilizer source and placement. The banding did not result in significantly higher CO_2 equivalents (133.44 μmol m^{-2} min^{-1}) than the surface applied fertilizers (107.29 μmol m^{-2} min^{-1}); although a trend ($P < 0.1$) was present for the banding to have higher CO_2 equivalents than the surface applied fertilizers. In addition, the poultry litter had a significantly higher CO_2 equivalent (153.23 μmol m^{-2} min^{-1}) than did the control (103.85 μmol m^{-2} min^{-1}), UAN (100.82 μmol m^{-2} min^{-1}), and the AN (80.64 μmol m^{-2} min^{-1}).

DISCUSSION

Carbon dioxide measurement

Tillage was observed to increase CO_2 flux in our study for 27% of the sampling dates, however, average flux was not significantly different during the growing season in this dry year, which may have mitigated the tillage effect during much of the growing season (Table II). Tillage impacts on CO_2 flux have been observed by others (Álvaro-Fuentes *et al.*, 2007; Chatskikh and Olesen, 2007). This increased CO_2 flux observed under CT is most likely due to increased microbial respiration mediated by soil tillage. Microbial respiration is increased through incorporation and mixing of crop residue in the plow layer, increased soil temperature and aeration, and macroaggregate turnover exposing soil organic matter to attack by microorganisms (Álvaro-Fuentes *et al.*, 2007). These products of tillage lead to increased microbial respiration, thereby resulting in more CO_2 being released from the soil. In addition, we observed a temporal impact on fluxes; the soil CO_2 flux increased dramatically in the warmer portion of the season (Fig. 1, Table IV). Temporal impacts on soil CO_2 flux observed through the growing season reported previously by others (Shimizu *et al.*, 2009) have been attributed to tillage increasing soil temperatures and subsequent microbial respiration which increased soil CO_2 flux.

In addition to tillage, our data suggest the possibility of fertilizer source having a significant impact on soil CO_2 flux (Fig. 1b, Table III). The highest soil CO_2 fluxes observed were in treatments using poultry litter as the N source. Relatively high CO_2 flux has also been observed when other animal manures are used as fertilizer sources (Shimizu *et al.*, 2009), which is similar to our observation with the use of poultry litter. This is most likely the result of microorganisms mineralizing the organic matter in the poultry litter. Inorganic fertilizes reduced or had no impact on soil CO_2 flux (Fig. 1b, Table III), which has been reported by other investigators (Fog, 1988; Hu *et al.*, 2004; Jones *et al.*, 2005; Lee *et al.*, 2007; Shimizu *et al.*, 2009) and is most likely due to the abundant available N from addition of inorganic fertilizers. The high abundance of available N decreased the need for soil microorganisms to mineralize soil organic matter to obtain the necessary N for growth and reproduction.

In addition to tillage and fertilizer source, our results suggested the possibility that fertilizer placement (banding) had a significant impact on fluxes (Fig. 1b, Table III). Banding of fertilizer sources showed a trend ($P < 0.1$) of increased soil CO_2 flux on 45% of the sampling dates particularly late in the growing season (Table V). When measuring soil moisture, it was observed (although not quantified) that the moisture content inside of the band was higher than the moisture content outside of the band. This was most likely due to the hydrophilic nature of urea-ammonium nitrate and the high water holding capacity of poultry litter. With increased soil moisture content, microbial respiration was most likely increased, resulting in a significant increase in soil CO_2 flux when fertilizer was band applied.

Methane measurement

Although we did not find many significant differences in CH_4 flux throughout the sampling season, we did observe that in general treatments had an average negative flux of CH_4 during the season, suggesting that those treatments may act as CH_4 sinks rather than sources (Fig. 2, Table II). Other investigators have reported that methane can be absorbed by oxidized soil (Bouwman, 1990; Le Mer and Roger, 2001; Liu *et al.*, 2008), so the findings of our study support these earlier reports. Soils with relatively low redox potentials have relatively high CH_4 emissions (Wang *et al.*, 1993; Yu *et al.*, 2001; Bennicelli *et al.*, 2006; Stepniewski and Stepniewska, 2009). The low redox potentials required for CH_4 emissions were not reached by the soils in this experiment. However, the redox potential has been shown to be lower in the center of aggregates (Zausig *et al.*, 1993), resulting in some CH_4 flux from soils that are not anoxic. In this case, the majority of CH_4 fluxing from the center of the aggregates is mostly likely absorbed by the oxidized soil surrounding the aggregate as it migrates away from the center, resulting in very low or negative fluxes of CH_4 from these soils as was observed in this study.

Nitrous oxide measurement

Over the entire growing season, significant differences in soil N_2O flux were observed for fertilizer source and placement (Fig. 3b, Table II), suggesting the possibility that these fertilizer management practices can influence greenhouse gas emissions. On one sampling date (9% of total sampling dates, June 4), a significant difference in soil N_2O flux was observed between CT and NT (Fig. 1a). However, when averaged across the entire growing season there were no significant differences between soil N_2O flux for CT and NT. This observation is supported by the literature as several authors have reported higher fluxes in NT fields (Lal *et al.*, 1995; Jacinthe and Dick, 1997), while others have reported higher fluxes of soil N_2O in CT fields

(Elder and Lal, 2008). Our results do not support a significant difference in soil N_2O flux based on tillage practice (Fig. 3a, Table II). This observation was likely caused by the low soil moisture content, resulting from low rainfall and sandy nature of the soil experienced throughout the sampling season.

Soil N_2O flux occurs through two main processes: denitrification (under anoxic conditions) and nitrification (under oxic conditions) (Glinski and Stepniewski, 1985). Often N_2O emissions are highest when soil first becomes wet as seen immediately following a rain event in an oxic soil. Other conditions that favor soil N_2O flux are: 1) availability of a suitable substrate (nitrogen); 2) increased soil temperature; 3) increased soil moisture; 4) finer soil texture; and 4) increased organic carbon. Nitrous oxide emissions from soils have been observed to be higher in organically fertilized plots (Kaiser and Ruser, 2000) most likely due to increased microbial biomass and the availability of a suitable C pool for mineralization. This is also likely the reason for the significantly higher soil N_2O flux observed on 73% of the sampling dates in plots fertilized with poultry litter in this study (Fig. 3b, Table III). In addition, McTaggart *et al.* (2002) observed higher soil N_2O fluxes when poultry litter was used in comparison to swine manure and urea. In our plots, not only was microbial biomass most likely increased with the addition of poultry litter, but we also applied an organic fertilizer rich in N that has been observed to increase soil N_2O flux by other investigators (Mosier *et al.*, 1998; Mosier *et al.*, 2001; Venterea *et al.*, 2005). These two factors most likely resulted in the high soil N_2O fluxes observed in these treatments. It is interesting to note that the inorganic treatments had relatively low N_2O fluxes in this study, indicating that denitrification didn't take place to any significant extent in these soils without the addition of an organic material, although in a wetter growing season this may not have been the case.

In addition to fertilizer source, fertilizer placement significantly impacted soil N_2O emissions on 45% of the sampling dates (Table V) with higher emissions coming from the fertilizers that were band applied, suggesting that fertilizer placement can influence soil N_2O flux. As mentioned in the discussion of CO_2 emissions, it was observed that the band had higher moisture content than the surrounding soil and this observation also helps explain the observed higher N_2O flux associated with fertilizer banding.

CO_2 equivalents

When looking at the overall impact that the soil flux of these gases has on CO_2 equivalent loss, it was observed that tillage did not impact the CO_2 equivalent. However, we did find that fertilizer source and placement showed a trend towards impacting CO_2 equivalent. These differences are driven by the high CO_2 and N_2O fluxes observed in the poultry litter fertilizer treatments and the treatments that were band applied. The procedure used to calculate effective flux from banded treatments corrects for the large portion of the soil surface that is not part or immediately adjacent to the band. The procedure allows for a direct comparison of the band application method compared to a broadcast method so that each can be measured on an area basis for which they are fertilizing the crop. Flux from the band has to be corrected so that the large area between bands, not impacted by the bands, does not get the same weight on an area basis as compared to a broadcast application. The procedure has been peer reviewed in a journal and is being used extensively by many scientists who are dealing with this issue of banding of fertilizers.

CONCLUSIONS

Conservation practices, such as no-tillage systems, can significantly reduce the magnitude of the CO_2 loss, thus minimizing agriculture's contribution to the gaseous losses of CO_2. In addition, fertilizer source and its placement can also significantly impact the amount of N_2O and CO_2 contributing to the overall CO_2 equivalents lost. Significant differences were found in fertilizer sources as well as fertilizer placement in terms of emissions of these two important greenhouse gases. Although our results suggest that fertilizer source and placement may be important in CO_2 equivalents lost from the soil (in the form of CO_2, CH_4, and N_2O) further research should be conducted on this topic to verify results and provide data that could be used for modeling and regulatory applications. CH_4 soil flux was not shown to be significantly different between treatments, but most of the treatments appeared to be sinks rather than sources of CH_4. Taken together, the overall CO_2 equivalent loss was not impacted by tillage, but was impacted by fertilizer placement and fertilizer source. Band applied fertilizer and poultry litter increased the CO_2 equivalent loss from the soil, but these results should be confirmed with higher sampling intensity across multiple years. These results are valuable in that they suggest that fertilizer source and placement can impact greenhouse gas emissions and suggest further research into this important issue.

These results raise other important questions. Specifically, are the emissions associated with poultry litter greater than, less than or equal to the emissions that would be associated with the poultry litter if it were not used as a fertilizer source? In addition, would a deeper placement or lower rates of the fertilizer applied by subsurface banding reduce the soil efflux of these important greenhouse gases? These are questions that we plan to pursue in future studies.

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