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Agroecosystem Management Effects on Greenhouse Gas Emissions Across a Coastal Plain Catena

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Abstract: Landscape variability influences soil properties that influence soil respiration and subsequent trace gas emissions. Scarcity of data on greenhouse gas emissions as influenced by landscape variability and agroecosystem management in southeastern United States necessitates study. The objective of this study was to evaluate effects of landscape variability and agroecosystem management on methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions on a Coastal Plain catena (Typic, Oxyaquic, and Aquic Paleudults) in Alabama. Soil management strategies included (i) conventional tillage (CT), (ii) conservation tillage (CsT), (iii) CT with dairy manure (CTM), and 4) CsT with dairy manure (CsTM) on a corn (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.) rotation. Each soil management treatment was replicated on summit, sideslope, and the drainageway landscape position. Gas measurements were conducted using a closed chamber method. The drainageway emitted 46, 251, 59, and 185 mg CH_4-C ha^{-1} h^{-1} from CT, CTM, CsT, and CsTM treatments, respectively. The summit position had fluxes of -59 and -90 mg CH_4-C ha^{-1} h^{-1} on CT and CsT treatments, respectively. Averaged across seasons, CT and CsT N_2O fluxes were similar (547 and 437 mg N_2O-N ha^{-1} h^{-1}, respectively) in the drainageway landscape position. Winter 2005 CO_2 emission from CsT treatments (averaged across landscape positions) was 1304 g CO_2-C compared with 227 g ha^{-1} h^{-1} CO_2-C from CT treatments.

Key words: Greenhouse gas emissions, landscape variability, soil management

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Increase in atmospheric greenhouse gas (GHG) concentrations is currently a concern because of their role in climate change. Concentration of these gases in the atmosphere has increased since the beginning of large-scale industrialization in the 1750s (IPCC, 2001). Agriculture alone contributes about 20% of the annual increase in radiative forcing (ability of 1 metric ton of a GHG to trap heat relative to a ton of carbon dioxide [CO_2]) through emission of methane (CH_4), nitrous oxide (N_2O), and CO_2 (Cole et al., 1997). An additional 13% annual increase from land clearing via burning raises this contribution to about 33%. To a large extent, emission of these gases depends on agroecosystem management and soil properties. Soil properties are a product of soil-forming factors including landscape variability, agroecosystem management, and climatic factors. Development and promotion of soil management practices that are maximizing CH_4 and CO_2 sinks while minimizing N_2O and CO_2 emissions and maintaining crop yields are required to reduce agriculture's contribution to climate change.

Carbon dioxide is produced from soil through respiration by plant roots, and micro– and macro–flora and fauna. Its production is a result of biochemical processes that are influenced by soil environmental factors (Hamada and Tanaka, 2001). Tillage operations increase CO_2 emission (Al-Kaisi and Yin, 2005). The magnitude of CO_2 emission from soil caused by tillage is highly correlated to intensity of soil disturbance (Reicosky, 1997). Mixing soil during plowing buries surface residues and aerates soil, favoring maximum CO_2 emission because of increased microbial respiration and CO_2 diffusivity. Inversion tillage results in increased CO_2 emission, with emission levels gradually declining with time (Reicosky, 1997).

Methane is second to CO_2 in its role of producing and enhancing the greenhouse effect (Lowe, 2006), with global warming potential of 23 (IPCC, 2001). In 2006, CH_4 contributed 7.9% of the total GHG in the United States (EPA, 2008). The rate of CH_4 oxidation in soil is influenced by diffusion of the gas to the microorganisms. Soil tillage has been found to decrease CH_4 oxidation (Six et al., 2004; Keller et al., 1990; Chan and Parkin, 2001). Lower rates of CH_4 oxidation in cultivated soils may be caused by a disturbance of the ecological niche for methanotrophic bacteria (Willison et al., 1995). Long-term application of farmyard manure has been found to inhibit CH_4 oxidation (Hütsch, 2001) because of the presence of NH_4 that is toxic to CH_4-oxidizing bacteria. Low-laying landscapes have been observed to act as net CH_4 emitters, whereas higher elevations were observed to act as net CH_4 consumers (Chan and Parkin, 2001). This is related to soil moisture content. Boeckx et al. (1996) observed optimum CH_4 oxidation at 15% wt/wt water content. Similarly, Xiu-Jun et al. (2000) and Cai and Yan (1999) found that moist soil oxidized CH_4, whereas dry soil did not. Chan and Parkin (2001) observed positive CH_4^+ fluxes at lower elevations and negative fluxes on higher elevations.

Nitrous oxide is a GHG that is produced by activities of microorganisms during denitrification and nitrification (Davidson, 1992). Nitrification converts ammonia to nitrate, whereas denitrification converts NO_3^- into N_2O. Nitrous oxide is involved in the destruction of stratospheric ozone (O_3) (Cicerone, 1987). It reacts with oxygen to form nitric oxide (NO) that catalyzes O_3 destruction. According to the Intergovernmental Panel on Climate Change (IPCC, 2001), N_2O has a global warming potential of 296. It contributed 5.2% of total GHG emissions in the United States in 2006 (EPA, 2008). Nitrous oxide emissions may be higher under no-till operations compared with cultivated soils (Six et al., 2004) because of a higher soil moisture content that favors denitrification. Emissions have been found to be higher on lower elevations compared with higher elevations (Sehy et al., 2003; Farrell et al., 2003). Sehy et al. (2003) found higher N_2O emissions on foot slope positions compared with shoulder positions. They attributed the difference to a higher water filled porosity (>60%) at the foot slope position resulting from lateral downslope water movement. Farrell et al. (2003) also found higher N_2O emissions on lower lying landscape positions.

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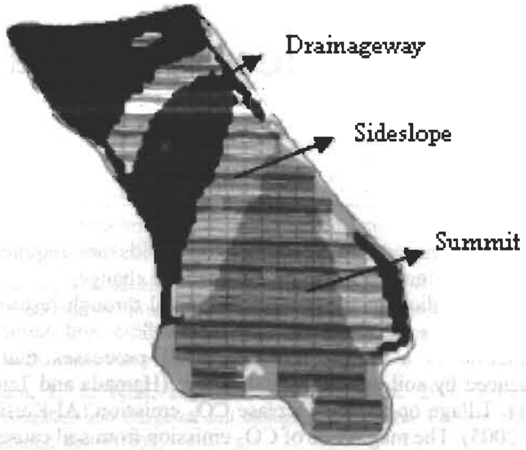

FIG. 1. Study site soil landscape positions created using fuzzy k-means unsupervised clustering based on soil SHWT, elevation, slope, and CTI. Summit is the highest position, drainageway is the lowest position, whereas sideslope is the more eroded landscape.

Soil C and N dynamics are largely influenced by topography and soil texture (Hook and Burke, 2000). Most C and N dynamics studies have observed higher C and N mineralization on lowlands compared with uplands (Hook and Burke, 2000; Groffman, 1998; Morris and Boerner, 1998). Scowcroft et al. (2004) observed faster nitrification on drainage bottoms compared with higher landscape positions. High soil moisture on lower slopes in forested areas was observed to result in lower N mineralization compared with upland positions (Ohrui et al., 1999). Soil C and N are the sources of soil N_2O, CH_4, and CO_2 emissions. Because field GHG emissions are expensive to measure, modeling emissions using data such as those obtained from the current study can be useful in predicting emissions on agricultural systems.

Data on emission of GHG in the southeastern United States, particularly in relation to landscape variability and agroecosystem management, are lacking. The objective of this study was to evaluate the effect of tillage, fall dairy manure application, and landscape variability on soil CH_4, N_2O, and CO_2 emission. Greenhouse gas emission field measurements are expensive to measure. Emission data obtained from this study can be used to predict emissions on row cropping systems as has been done on paddy rice production ecosystems (Mosier et al., 2004). The data may also be useful in validating existing gas emission models.

MATERIALS AND METHODS

Study Site

The study site is at the E. V. Smith Research Center near Shorter, Alabama, and lies at 85°53′50″W and 32°25′22″N. The site has a gentle slope ranging from 0% to 5%, and the soils are Typic, Oxyaquic, and Aquic Paleudults. Surface soil chemical characteristics before experiment establishment (2000) at the site have been described by Terra et al. (2006).

Soil Management and Experimental Design

The study site is a 9-ha field containing a corn-cotton rotation. Soil management treatments were established in 6.1 m wide by approximately 240-m-long strips across the landscape (Fig. 1) in a randomized complete block design with six replications. Plots measuring 6.1 m × 18.3 m were delineated in each strip, resulting in a total of 496 plots. Soil management treatments implemented in Fall 2000 included: (i) conventional tillage (CT) involving disking, chisel plowing (to a depth of 40 cm), and field cultivation; (ii) conventional tillage + dairy manure (CTM) applied once each fall at a rate of approximately 10 Mg ha^{-1} (fresh weight basis); (iii) conservation tillage (CsT) consisting of noninversion in-row subsoiling and winter cover crops of white lupin (*Lupinus albus* L.) and crimson clover (*Trifolium incarnatum* L.) before corn and rye (*Secale cereale* L.)/black oat (*Avena strigosa* Schreb.) mixture before cotton; and (iv) conservation tillage + dairy manure (CsTM) applied in the fall at a rate of approximately 10 Mg ha^{-1}. Experiment treatments were reported by Terra et al. (2006).

The field was divided into three soil landscape positions (Fig. 1) using a detailed soil survey (1:15,000) and a high-resolution digital elevation model (DEM) (Terra et al., 2006). Digital elevation data were obtained using a real-time kinematic–global positioning system. Elevation data were interpolated to provide a DEM in Arc Info (ESRI, Redlands, CA) and used to develop the slope and the compound topographic index (CTI). The CTI was hypothesized to be a useful factor in delineating areas of the field of similar wetness. The index has been found to be highly correlated with several soil attributes (Moore et al., 1993). It is calculated using a specific catchment area and slope (Moore et al., 1993):

$$CTI = \ln (SCA/S°) \qquad (1)$$

where SCA, specific catchment area
S°, slope (%)

Soil survey data were rasterized to indicate depth to a seasonal high water table (SHWT) and overlain with DEM, slope, and CTI layers. Fuzzy k-means unsupervised clustering of these multivariate data were used to delineate three landscape positions (summit, sideslope, and drainageway) (Fridgen et al., 2004).

In Spring 2004, 36 global positioning system–referenced plots were identified for trace gas measurements. Plots were distributed across the three landscape positions and four management systems cropped to cotton during 2004. These plots were under corn rotation in 2005 and under cotton in 2006. Each management treatment was replicated three times (3 × 4 × 3 = 36 plots).

Dairy manure was applied on October 22, 2004, and November 19, 2005. On CT plots, chisel plowing and disking were performed on April 29, 2004, and April 15, 2005, respectively. Selected manure properties are shown in Table 1.

Gas Measurement

Gas measurements were taken eight times in a 2-year period using the static closed chamber method described by Mosier and Schimel (1991). Gas samples were obtained on May 12, 2004, August 5, 2004, October 27, 2004, January 20, 2005, April 29, 2005, July 22, 2005, November 7, 2005, and January 26, 2006. Chambers were constructed from 20-cm-diameter polyvinyl chloride pipes and were 16 cm in height. They were composed of a lower base and an upper detachable cap with top surface lined with reflective foil to maintain ambient air temperature in the chamber headspace. The bottom edge was sharpened to facilitate chamber installation and minimize or prevent soil compaction. The cap was fitted with a 5-mm diameter vent and a removable gray butyl rubber septum sampling port. A day before gas sample collection, the chamber base was pushed into the soil to a depth of 3 cm, leaving the rest of the chamber above the soil surface and open to the atmosphere. Chambers were placed on the middle nontrafficked parts of the plot in between corn or cotton rows depending on season. At the start of the gas sample collection, chamber caps were placed on each base and held in place with a latex elastic band. Gas was sampled at 0, 30, and 60 min.

TABLE 1. Selected Manure Properties

Manure Application Date	Total Nutrients (g kg^{-1}), %					
	N	P	K	Ca	Mg	MC
October 22, 2004	8.2	3.4	1.3	2.9	8.9	44
November 19, 2005	6.2	0.9	0.9	7.8	2.1	70

To represent daily average temperatures at the site, gas samples were taken during the midmorning. Three milliliters of gas were collected from the chamber headspace using a 3-mL disposable syringe equipped with a needle. To ensure a representative sample from the chamber, the syringe was pumped three times to mix the gas in the chamber headspace before taking out a sample. Samples were transferred to 3-mL glass storage vials, stored at 4°C, and transported to the laboratory where they were stored at the same temperature until analysis. Before gas sampling, storage vials were capped with gray butyl rubber septa at the gas sampling site to ensure similar background conditions in the vials and the sampling site. At each sampling time, two samples were obtained. One sample was used for CH_4 determination, whereas the other was for N_2O and CO_2 analyses.

Gas samples were analyzed using a Varian Star *cx* gas chromatograph (Varian, Walnut Creek, CA). Nitrous oxide and CO_2 were determined in turns (from one vial) using a 4-m Haysep R column and a ^{63}Ni electron capture detector. The detector temperature was 350°C, and the carrier gas was N_2 (17 mL min^{-1} flow rate). Methane concentrations were determined using a 3-m Porapak N column and a flame-ionizing detector. The detector temperature was 350°C, and the carrier gas was N_2 at a flow rate of 30 mL min^{-1}. Calibration curves were generated using respective gas standard samples, and CH_4, N_2O, and CO_2 fractions (by volume) were calculated from the peak area in the chromatograms.

At each gas sampling time, soil temperature was determined on one plot per replication using HOBO® Temperature Probes (Forestry Suppliers Inc, Jackson, MS).

Gas Flux Calculations

Gas flux calculations were based on chamber volume and soil surface area covered by the chamber. Gas volume at standard temperature and pressure was assumed in the calculations (22.4 L mol^{-1}). Chamber head space internal volume above the soil surface was 4.08 L calculated from a chamber diameter of 0.2 m and a height of 0.13 m above the soil surface. Chamber volume occupied by each gas was calculated from the gas concentration obtained from the gas chromatography analysis and subsequently used to determine the number of moles of each gas in the chamber at the time of sampling using the ideal gas law. This was further converted to mass of C in the case of CH_4 and CO_2, and N for N_2O, and expressed on soil area basis. Gas flux was determined by linear regression of time of gas accumulation against respective mass per unit area. According to Hutchinson and Mosier (1981), during short periods, biological gas production can be considered to be constant. In that case, the only correction needed was correction for decrease in soil gas concentration over time. This correction was only useful when the change in gas concentration between subsequent sampling times was positive because the natural log (ln) is a component of the factor. Use of linear regression assumes uniform gas concentration throughout the chamber headspace, constant gas concentration near the upper limit of production zone, and linear increase in gas concentration with depth (Hutchinson and Mosier, 1981).

Soil Sampling and Analysis

At each gas sampling time, soil samples were obtained from 0- to 5-cm depth using a 2.0-cm-diameter hand probe. On each plot, 20 samples were obtained in a random manner and combined to form one composite sample per plot. Samples were stored at 4°C until analysis for mineral N (NH_4–N and NO_3-N). This was determined by extraction with 2 *M* KCl at a ratio of 1:5 (soil:KCl), and concentrations of NH_4^+ and NO_3^- were determined colorimetrically using a μQuant™ microplate spectrophotometer (BioTek Instruments, Inc, Winooski, VT). Organic soil C and total N were determined on dry soil using LECO TruSpec CN analyzer (Leco Corp, St Joseph, MI). Gravimetric soil moisture content was determined by drying 1 g of soil at 105°C to constant weight.

Data Analysis

PROC MIXED in SAS (SAS Institute, Cary, NC) was used to account for repeated measures across seasons and to test for main effects and interactions of CH_4, N_2O, and CO_2 fluxes. Treatment means were compared using least significant difference calculated from SE obtained from the PROC MIXED procedure. Treatment means were compared using Fisher protected least significant difference at $P \leq 0.05$.

Stepwise regression was used to relate terrain attributes to gas emissions in seasons when significant soil management (tillage and dairy manure) effects were observed. The probability of the statistic F to enter a variable was 0.25, whereas the probability to retain a variable in the model was at 0.15. Terrain attributes used in the regression analysis are shown in Table 2 (Terra et al., 2006).

RESULTS

Landscape Variability

Mean values of soil properties and terrain attributes are shown in Table 2. Highest elevations and depth to SHWT were found on the summit landscape position. Positive profile curvature values on the summit landscape position indicate a convex profile, whereas a negative profile curvature within the

TABLE 2. Mean Landscape Variability Factors Among Summit, Drainageway, and Sideslope Landscape Positions at E. V. Smith Research Center Near Shorter, Alabama

Terrain Attribute	Soil Landscape Position		
	Summit	Sideslope	Drainageway
CTI	3.98b	4.15	6.16
Elevation, m	71.33	70.53	69.49
Planimetric curvature	0.01	−0.01	−0.08
Profile curvature	0.02	0.02	−0.09
Slope, %	0.60	3.33	1.33
Flow accumulation	5.01	7.13	30.35
SHWT, cm	145.83	108.33	75.00
Sand†, %	56.78	54.32	63.75
Silt, %	24.44	25.50	25.20
Clay, %	18.79	21.12	11.06

†Surface horizon sand, silt, and clay content.

drainageway indicates a concave profile (Li et al., 2005). Sideslope landscape position had higher slope, surface horizon clay content, and profile curvature (more convex shape) compared with the drainageway position. Higher flow accumulation within the drainageway suggests higher soil moisture content.

Methane Fluxes

Samples for CH_4 flux determination were seasonally collected between Spring 2004 and Winter 2006, but only Spring 2004 fluxes are reported because of gas chromatography CH_4 channel failure in subsequent seasons. There were no significant differences in CH_4 fluxes between soil management treatments and landscape positions (Fig. 2). On summit landscape position, CTM had an average of 8 mg CH_4-C ha^{-1} h^{-1}, whereas CsTM had an average flux rate of 310 mg CH_4-C ha^{-1} h^{-1}. Methane fluxes in the drainageway were 46, 251, 59, and 185 mg CH_4-C ha^{-1} $h^{-1}$from CT, CTM, CsT, and CsTM, respectively.

Nitrous Oxide Fluxes

A soil management by season interaction (P = 0.031) revealed N_2O flux differences in Spring 2004 and Fall 2005. In spring, CT and CsT had similar fluxes, but fluxes were higher from CsT and CsTM treatments. In the fall, CsT had greater N_2O fluxes than CT treatment. Dairy manure decreased N_2O flux on CsT treatments (CsT and CsTM). In both seasons, terrain attribute effects on N_2O fluxes varied with soil management (Table 3). In Spring 2004, slope had a negative effect on N_2O flux on CTM treatments. Surface horizon clay content explained 71% (R^2 = 0.709) of N_2O flux variability on CTM treatments.

Soil management interacted with landscape position (P = 0.037) to affect N_2O-N fluxes. Significant soil management treatment differences in N_2O-N flux were observed only in the drainageway (Fig. 3). Averaged across soil management treatments and seasons, average N_2O-N flux in the drainageway was 346 mg ha^{-1} h^{-1} N_2O-N relative to 158 and 220 mg ha^{-1} h^{-1} N_2O-N on the summit and sideslope, respectively. Within the drainageway, no N_2O-N flux differences were observed between the two tillage systems, but fluxes were higher on CT than on CTM and CsTM treatments (Fig. 3). Thus, within the CT system, dairy manure application (CTM) decreased N_2O flux, although it had no significant effect on CsT system fluxes.

A significant season by landscape position interaction (P = 0.002) indicated that N_2O flux differences occurred in Spring and Fall 2004 (Fig. 4). In spring (Fig. 4A), highest fluxes were observed on the summit landscape position, whereas in fall (Fig. 4B), higher fluxes were in the drainageway.

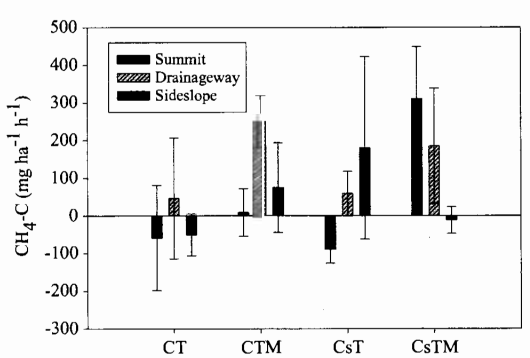

FIG. 2. Methane fluxes on three soil landscape positions at E. V. Smith Research Center near Shorter, Alabama. Bars represent SEM.

TABLE 3. Stepwise Regression Relating Landscape Variability Factors to N_2O Flux

Season	Soil Management Treatment	Independent Variable†	Partial R^2	P
Spring 2004	CT	Sand (+)	0.393	0.071
	CTM	Slope (−)	0.459	0.045
	CsT	SHWT (+)	0.478	0.039
	CsTM	SHWT (+)	0.559	0.021
Fall 2005	CT	CTI (+)	0.485	0.037
	CTM	Clay (−)	0.709	0.004
	CsT	None	NS‡	NS
	CsTM	Profile curvature (+)	0.295	0.131

Only variables with the highest significant contribution to flux variability in each soil management treatment are shown. A positive sign (+) indicates that an increase in the given variable causes an increase in N_2O flux, whereas a negative (−) sign indicates the opposite.

†SHWT: seasonal high water table; CTI: compound topographic index; sand, surface horizon sand content; clay, surface horizon clay content.

‡Not significant at ≤0.15.

Carbon Dioxide Emission

Season and soil management interacted to alter CO_2 emission (P = 0.001). Significantly different CO_2 emissions were observed in Winter 2005, when CsT treatments had higher emission (1304 g ha^{-1} h^{-1} CO_2-C) than CT treatments (227 g ha^{-1} h^{-1} CO_2-C). A similar trend was observed in Winter 2006 when CsT emitted 1151 g ha^{-1} h^{-1} CO_2-C compared with 390 g ha^{-1} h^{-1} CO_2-C on CT treatments.

Effect of landscape variability on winter CO_2 emission varied among soil managements (Table 4). On CT treatments, CO_2 emission was positively influenced by factors that favor increased soil moisture. Flow accumulation increased CO_2 emissions, whereas slope had a negative effect on CO_2 emissions. Lowest slopes were found in the drainageway landscape position that also had higher soil moisture. Whereas higher slope favored CO_2 emissions on CsTM treatments in Winter 2006, it also negatively influenced emissions on CsT treatments in the same season. In Winter 2005, surface horizon

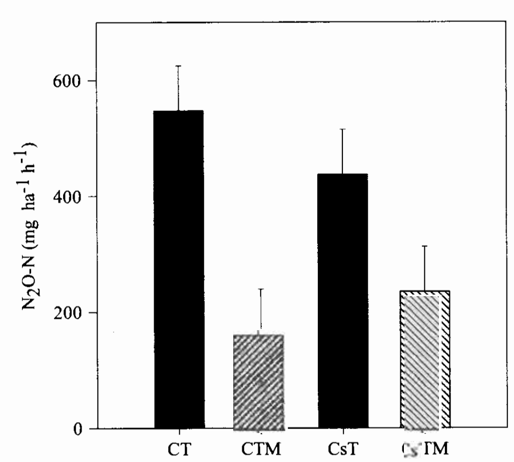

FIG. 3. Soil N_2O fluxes from drainageway landscape positions averaged across seasons. Bars represent SEM.

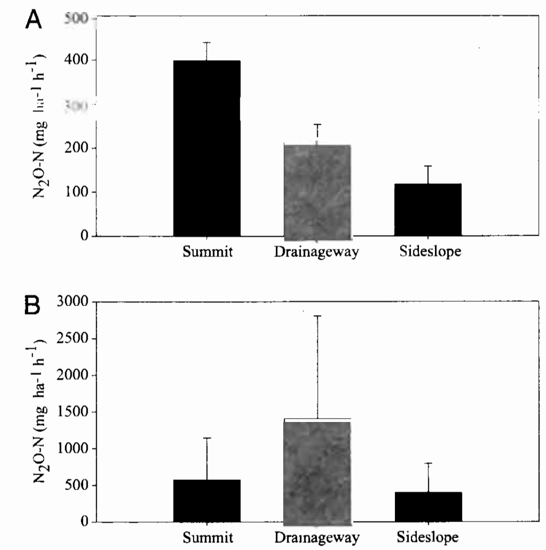

FIG. 4. Soil N_2O flux as influenced by landscape position and season in Spring 2004 (A) and Fall 2004 (B). Bars represent SEM.

sand content had a positive influence on CO_2 emission on CTM treatments, and 83% (R^2 = 0.834) of the emission variation could be attributed to this factor. Flow accumulation explained 71% (R^2 = 0.710) of CO_2 emission on CT treatments, but none of these factors contributed significantly to CO_2 emission on CsTM treatments. In Winter 2006, the main terrain attribute influencing CO_2 emission was slope. Slope explained 29% (R^2 = 0.286) and 28% (R^2 = 0.276) of CO_2 emission variability on CT and CsT treatments, respectively.

Soil Variables

There were significant season by landscape position by soil management interactions for soil NH_4-N (P = 0.001). Summit and sideslope landscape positions had similar but higher soil NH_4-N in CT treatments in most seasons (Fig. 5) compared with other tillage treatments. However, CT treatments had lower NH_4-N within the drainageway landscape position. Dairy manure tended to decrease NH_4-N in most seasons within summit and sideslope landscape positions, but not on the drainageway.

Significant season by soil management (P = 0.001) interaction effects on soil NO_3-N were observed in all seasons except Spring 2004, Summer 2004, and Winter 2005. In Fall 2004, dairy manure increased NO_3-N levels in both tillage systems. Highest seasonal NO_3-N levels were recorded in the spring of 2005, with CsT treatments showing higher NO_3-N (38 mg kg^{-1} soils) compared with CT treatment (13 mg kg^{-1} soils). In Spring 2005, dairy manure did not significantly affect NO_3-N levels in either tillage system. Similar trends were observed in Winter 2006.

There were significant seasonal differences (P = 0.001) and landscape position by soil management treatment interactions (P = 0.049) for total soil N. In Summer 2004 and Winter 2005, higher total N was found on summit landscape (2.05 and 2.07 g kg^{-1}, respectively) relative to the drainageway (1.20 and 1.07 g kg^{-1} on drainageway and sideslope, respectively) and sideslope (1.74 and 1.29 g kg^{-1} on drainageway and sideslope, respectively). In all seasons, CsTM treatment had the highest total soil N, whereas CT had the lowest levels (Fig. 6).

There were significant season by soil management interaction effects (P = 0.001) on total soil C in the surface 0 to 5 cm. Conservation tillage showed higher soil organic C (averaged across landscape positions) compared with CT in each season except in Summer 2004. Dairy manure increased soil organic C in both tillage systems in all seasons except Winter 2005 when dairy manure had no significant effect on soil organic C on CT (13.28 on CT compared with 15.21 g kg^{-1} on CTM). Within the CT treatments, total organic C was more or less constant throughout the 2 years. Averaged across all seasons, CsT treatments had 13.1 g C kg^{-1} soil compared with 7.6 g C kg^{-1} soil on CT treatments.

There were significant season by landscape position (P = 0.003) and season by soil management (P = 0.001) interactions on gravimetric soil moisture (0-5 cm). In all seasons, consistently higher soil moisture was found on CsTM treatments, whereas the lowest moisture levels were found on CT treatments (Fig. 7A). In addition, dairy manure increased soil moisture in both tillage systems. Higher water content was found in the drainageway, whereas similar water contents were observed on the summit and the sideslope landscape positions (Fig. 7B). These differences were observed in Fall 2004, Winter 2005, and Winter 2006.

DISCUSSION

Methane Fluxes

Although reduced tillage has been observed to increase CH_4 consumption by minimizing soil disturbance that is favorable to CH_4-oxidizing bacteria (Hütsch, 1997), CT did not reduce CH_4 consumption significantly compared with CsT treatments in our study. Hütsch (1997) found that sieving intact soil cores (5 mm) reduced CH_4 oxidation by 57% and 15% on sandy and loamy soils, respectively. Lower CH_4 oxidation on sandy soil was attributed to greater destruction of soil aggregates that reduce methane-oxidizing bacteria activity. Similar to our findings, Suwanwaree and Robertson (2005) found no effect of plowing on CH_4 oxidation along a management intensity gradient ranging from virgin forest to a no-till corn-soybean (*Glycine max* L.)-wheat (*Tritium aestivum* L.) rotation in Michigan.

TABLE 4. Stepwise Regression Relating Landscape Variability Factors to CO_2 Flux

Season	Soil Management Treatment	Independent Variable†	Partial R^2	P
Winter 2005	CT	Flow accumulation (+)	0.710	0.004
	CTM	Sand (+)	0.834	0.001
	CsT	Clay (−)	0.400	0.070
	CsTM	None	NS‡	NS
Winter 2006	CT	Slope (−)	0.286	0.138
	CTM	Silt (+)	0.370	0.083
	CsT	Slope (−)	0.276	0.147
	CsTM	Slope (+)	0.375	0.080

Only variables with the highest significant contribution to flux variability in each soil management treatment are shown. A positive sign (+) indicates that an increase in the given variable causes an increase in CO_2 flux, whereas a negative (−) sign indicates the opposite.

†Sand, surface horizon sand content; clay, surface horizon clay content; silt, surface horizon silt content.

‡Not significant at ≤0.15.

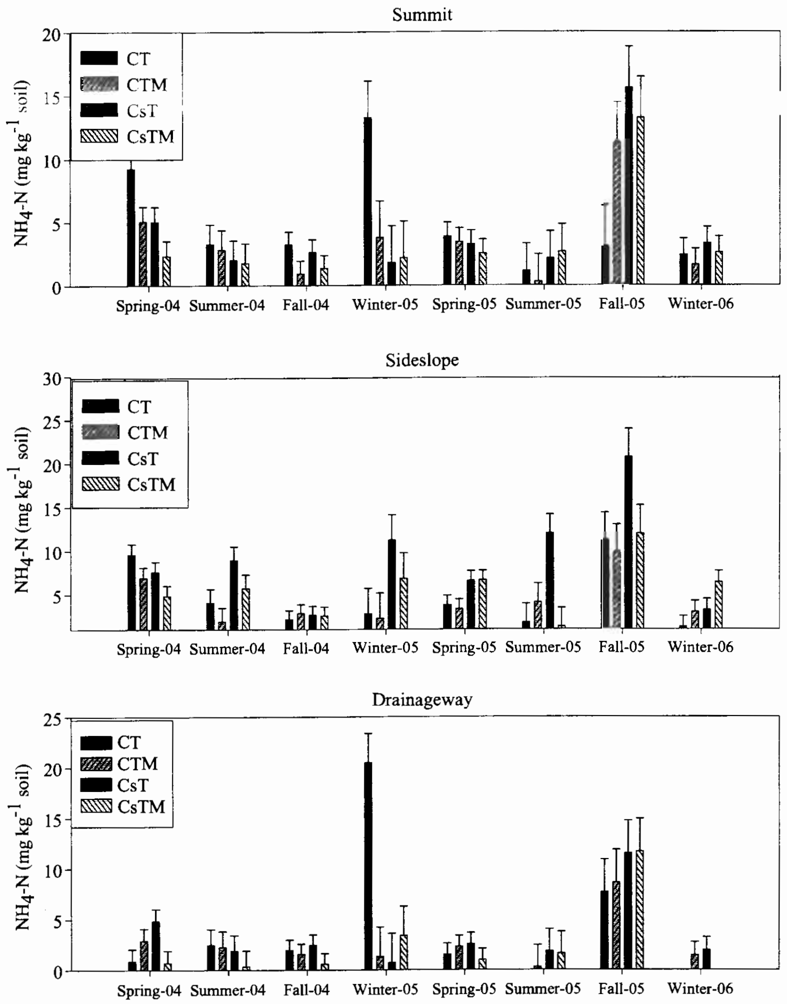

FIG. 5. Soil NH_4-N seasonal variation as affected by landscape position and soil management. Bars represent SEM.

Other factors, such as soil moisture and temperature, influence CH_4 fluxes. Laboratory studies have shown an optimum methane oxidation temperature of 20°C to 30°C (Boeckx et al., 1996). Optimum temperature decreased with increasing soil moisture. In our study, mean soil temperatures on both tillage systems were similar (27°C–31°C and 29°C–32°C on CT and CsT treatments, respectively), which may, in part, explain lack of CH_4 flux differences in the two systems. Soil

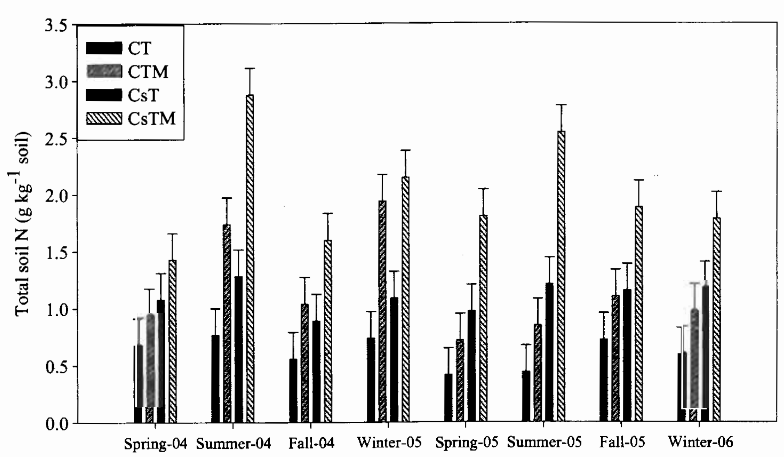

FIG. 6. Seasonal total soil N after 6 years of soil management. Data are averaged across soil management treatments. Bars represent SEM.

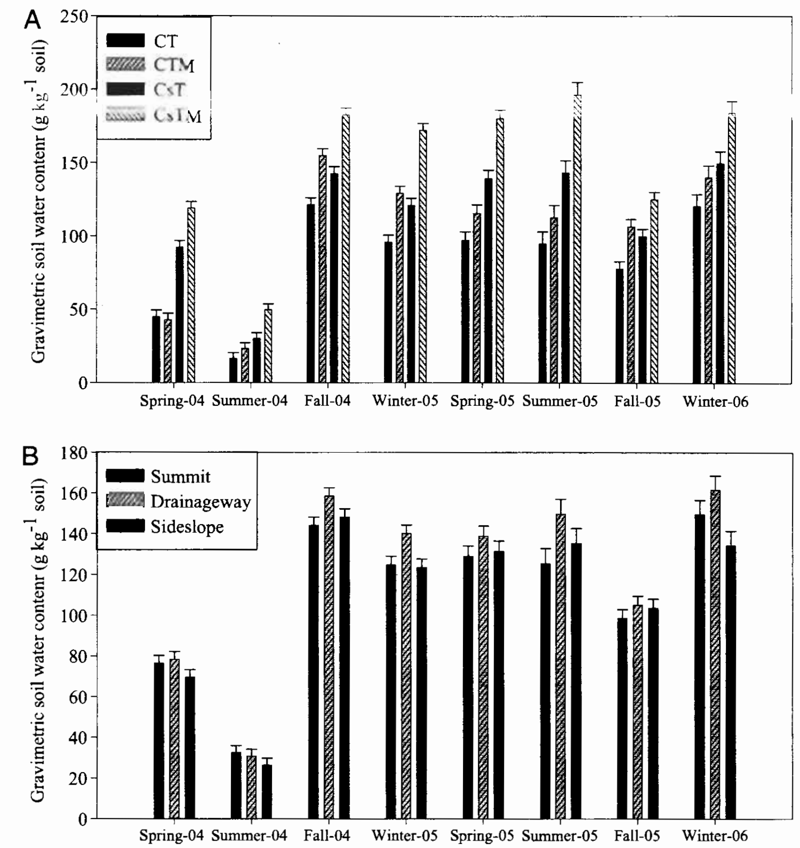

FIG. 7. Seasonal variation of gravimetric soil water content as affected by soil management (A) and landscape variability (B). Bars represent SEM.

moisture was also similar in both systems. Similarly, Chan and Parkin (2001) found no difference in fluxes between no-till and plowed sites. They attributed this to field spatial variation, but in our study, spatial variation was largely accounted for by stratifying the plots by landscape.

According to Venterea et al. (2005), the effect of tillage on CH_4 emissions depends on the type of N fertilizer used. In their study in Minnesota, urea ammonium-nitrate resulted in no differences in CH_4 emissions between tillage systems, whereas urea increased CH_4 emission on reduced tillage systems. In our study, no N fertilizer had been applied before gas measurements other than that applied to corn in the previous cropping season and 34 kg N ha^{-1} ammonium-nitrate applied to CsTM treatments 3 months earlier. It is important to note that tillage operations were done in early spring, whereas gas measurements were taken 13 days later. Effect of tillage on factors that control CH_4 fluxes may have diminished with time after cultivation.

Landscape variability influences CH_4 fluxes because of accompanying differences in soil properties that interact with soil management. This may result in different CH_4 flux responses at short distance intervals (local-scale variability) within a landscape. Soil temperature in the drainageway ranged between 27°C and 30°C. This temperature is within the range (20°C–40°C) at which most CH_4-producing bacteria operate (Meixner and Eugster, 1999). Chan and Parkin (2001) found positive CH_4 fluxes in low-laying areas and negative fluxes in higher areas in Iowa. This difference was partly caused by higher soil moisture in the lower landscape positions.

The main substrate in CH_4 production in soil is acetate and results from fermentation of several substances including organic matter (Meixner and Eugster, 1999). Decomposition of dairy manure can provide this raw material for CH_4 production. Lack of differences between manure and no manure treatments in CH_4 fluxes may be caused by the extended time between manure application (Fall 2003) and gas measurement (Spring 2004).

Nitrous Oxide Fluxes

Summit and sideslope landscape positions did not show soil management differences, perhaps because of similar soil moisture between soil management. Seasonal soil management treatment differences in N_2O-N flux observed in Spring 2004 and Fall 2005 (Fig. 4) correspond with seasons that had lower soil moisture (Fig. 7A) and higher soil NH_4-N (Fig. 5). Other than Summer 2004, when soil moisture was extremely low, Spring 2004 and Fall 2005 had the lowest gravimetric moisture contents. Highest soil NH_4-N levels over the entire study period were measured during these two seasons, suggesting that the N_2O measured was mainly a result of NH_4^+ nitrification. During the two seasons, N_2O fluxes were influenced by soil NH_4^+, as indicated by the similarity between N_2O flux (Fig. 3) and soil NH_4 trends (Fig. 5). Similarly, Breuer et al. (2002) found a positive correlation between nitrification and N_2O emission, and negative correlation between nitrification and increasing rates of water-filled porosity.

Lack of a significant tillage effect on N_2O flux within landscape positions may be caused by similar soil moisture and temperature between the tillage systems. Mean soil temperature (averaged across seasons) on each individual landscape position was between 20°C and 23°C. Higher mean N_2O flux on CsT compared with CT in Fall 2005 may be related to the relatively higher NH_4 and NO_3-N on these treatments compared with CT treatments in this season. Nitrous oxide is a product of NH_4 nitrification and denitrification of NO_3 (Meixner and Eugster. 1999). Both processes are controlled by oxygen concentration, but McSwiney et al. (2001) pointed out that high N_2O concentration in a location could be a result of gas production or gas accumulation.

Nitrous oxide fluxes seemed to negatively correlate with soil moisture, although the differences in these levels may not have been sufficient to result in significant soil management treatment differences. High soil moisture conditions can create reducing conditions, where N_2O is reduced to N_2. Low N_2O flux in Winter 2005 and 2006 may be a result of lower soil temperatures (a seasonal average of 9.8°C and 9.0°C, respectively) and relatively high soil moisture. The decrease in N_2O flux on the drainageway on CTM and CsTM treatments may be attributed to an accompanying increase in soil moisture.

In Spring 2004 and Fall 2005, when significant soil management treatment (tillage and dairy manure) effects on N_2O fluxes were observed within the drainageway, landscape variability effects on N_2O flux were not consistent. A positive relationship between surface horizon sand content (Table 3) and N_2O fluxes on CT treatments in Spring 2004 is consistent with a negative correlation between N_2O fluxes and soil moisture content during this season. Soils with high sand content generally have low amounts of available moisture. However, in Fall 2005, no single terrain attribute could reasonably explain N_2O flux variance on CsT treatments. High surface horizon clay content resulted in decreased N_2O fluxes on CTM treatments, perhaps because of its positive influence on soil moisture. Variation in effect of terrain attributes on N_2O fluxes across seasons may not be surprising, given that terrain attributes act interactively with environmental factors in their influence on microbial activities. Whereas terrain attributes may not change much during short periods, environmental factors are dynamic and a change in these factors is accordingly reflected in soil microbial activities.

Carbon Dioxide Emission

We observed a higher CO_2 emission under CsT than on CT treatments in winter, with no soil management treatment differences in other seasons. The reason for this observation is not clear because soil temperature and moisture levels were comparable in both systems. It may be caused by differences in gas diffusivity in the two systems as a result of differences in soil porosity. According to Hashimoto and Komatsu (2005), CO_2 flux is a function of CO_2 respiration and diffusivity. Soils managed under conservation tillage may be more porous because of annual addition of winter cover crop residues. Cover crops also would provide additional substrate during decomposition. Soil C:N ratio ranged from 9 to 15, levels at which net mineralization (with subsequent CO_2 release) would be expected. As expected, CO_2 fluxes were lowest in winter (on conventional tillage systems) and may be associated with low winter soil temperatures. Low CO_2 fluxes observed in Summer 2004 may be related to noticeably low soil moisture (Fig. 7A) and high soil and air temperatures (data not shown).

CONCLUSIONS

Greenhouse gas emissions showed seasonal variations across soil management treatments with higher CO_2 emissions from CsT than CT treatments. This suggests that although cover crops improve soil properties and increase soil nutrients, they may also increase CO_2 emissions during the winter season. Higher N_2O fluxes from CT treatments on drainageway landscape positions suggest that N_2O emissions may be somewhat mitigated by soil management strategies that minimize GHG emissions in wetter landscape positions. In addition. this study was conducted several days, and in some seasons, several months after tillage operations and dairy manure applications. It possible that effects of these operations on emissions declined with time. We suggest that gas measurements be done as soon as possible after management operations to capture gas emission changes that follow these operations. In addition, best management options such as timing of nitrogen fertilizer application according to actual needs (Wassmann and Vlek, 2004) and use of slow N release fertilizers (Mosier et al., 1998) should be encouraged.

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