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

Catherine N. Gacengo, Charles Wesley Wood, Joey N. Shaw, Randy L. Raper, and Kipling S. Balkcom

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 (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) emissions on a Coastal Plain catena (Typic Oxyaquolls, Aquic Paleudults) in Alabama. Soil management strategies included (i) conventional tillage (CT), (ii) conservation tillage (CTT), (iii) CT with dairy manure (CTM), and (iv) CTT with dairy manure (CTSM) 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 CH₄-C ha⁻¹ h⁻¹ from CT, CTT, CTM, and CTSM treatments, respectively. The summit position had fluxes of -89 and -90 mg CH₄-C ha⁻¹ h⁻¹ on CT and CTT treatments, respectively. Averaged across seasons, CT and CTT N₂O fluxes were similar (547 and 437 mg N₂O-N ha⁻¹ h⁻¹, respectively) in the drainageway landscape position. Winter 2005 CO₂ emission from CTT treatments (averaged across landscape positions) was 1304 g CO₂-C compared with 227 g ha⁻¹ h⁻¹ CO₂-C from CT treatments.

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

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 [CO₂]) through emission of methane (CH₄), nitrous oxide (N₂O), and CO₂ (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 CH₄ and CO₂ sinks while minimizing N₂O and CO₂ 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 CO₂ emission (Al-Kaisi and Yin, 2005). The magnitude of CO₂ 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 CO₂ emission because of increased microbial respiration and CO₂ diffusivity. Inversion tillage results in increased CO₂ emission, with emission levels gradually declining with time (Reicosky, 1997).

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Methane is second to CO₂ in its role of producing and enhancing the greenhouse effect (Lowe, 2006), with global warming potential of 23 (IPCC, 2001). In 2006, CH₄ contributed 7.9% of the total GHG in the United States (EPA, 2008). The rate of CH₄ oxidation in soil is influenced by diffusion of the gas to the microorganisms. Soil tillage has been found to decrease CH₄ oxidation (Six et al., 2004; Keller et al., 1990; Chan and Parkin, 2001). Lower rates of CH₄ 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 CH₄ oxidation (Hütsch, 2001) because of the presence of NH₄ that is toxic to CH₄-oxidizing bacteria. Low-lying landscapes have been observed to act as net CH₄ emitters, whereas higher elevations were observed to act as net CH₄ consumers (Chan and Parkin, 2001). This is related to soil moisture content. Bocek et al. (1996) observed optimum CH₄ oxidation at 15% w/w water content. Similarly, Xiu-Jun et al. (2000) and Cai and Yan (1999) found that moist soil oxidized CH₄, whereas dry soil did not. Chan and Parkin (2001) observed positive CH₄ 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 NO₃⁻ into N₂O. Nitrous oxide is involved in the destruction of stratospheric ozone (O₃) (Cicerone, 1987). It reacts with oxygen to form nitric oxide (NO) that catalyzes O₃ destruction. According to the Intergovernmental Panel on Climate Change (IPCC, 2001), N₂O 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 N₂O 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 N₂O emissions on lower lying landscape positions.
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 (Ohri et al., 1999). Soil C and N are the sources of soil N70, and C and N dynamics studies have observed higher C and N emission models.

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 CH4, N2O, and CO2 emission. Greenhouse gas emission field measurements 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.

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Soil Management and Experimental Design

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).

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 x 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):

\[ CTI = \ln \left( \frac{SCA}{S^o} \right) \]

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 x 4 x 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 high. They were composed of a lower base and an upper detachable cap with top

TABLE 1. Selected Manure Properties

<table>
<thead>
<tr>
<th>Manure Application Date</th>
<th>N (%)</th>
<th>P (%)</th>
<th>K (%)</th>
<th>Ca (%)</th>
<th>Mg (%)</th>
<th>MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 22, 2004</td>
<td>8.2</td>
<td>3.4</td>
<td>1.3</td>
<td>2.9</td>
<td>8.9</td>
<td>44</td>
</tr>
<tr>
<td>November 19, 2005</td>
<td>6.2</td>
<td>0.9</td>
<td>0.9</td>
<td>7.8</td>
<td>2.1</td>
<td>70</td>
</tr>
</tbody>
</table>

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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 to prevent soil compaction. The cap was fitted with a 5-mm 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 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 to prevent soil compaction in the vials and the sampling site. At each sampling time, two samples were obtained. One sample was used for CH4 determination, whereas the other was for N2O and CO2 analyses.

Gas samples were analyzed using a Varian Star cx gas chromatograph (Varian, Walnut Creek, CA). Nitrous oxide and CO2 were determined in turns (from one vial) using a 4-m Haysep R column and a 32Ni electron capture detector. The detector temperature was 350°C, and the carrier gas was N2 (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 N2 at a flow rate of 30 mL min⁻¹. Calibration curves were generated using respective gas standard samples, and CH4, N2O, and CO2 fractions (by volume) were calculated from 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 volume 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 CH4 and CO2, and N for N2O, 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 (NH4-N and NO3-N). This was determined by extraction with 2 M KCl at a ratio of 1:5 (soil:KCl), and concentrations of NH4⁺ and NO3⁻ 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 CH4, N2O, and CO2 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>
<thead>
<tr>
<th>Terrain Attribute</th>
<th>Summit</th>
<th>Sideslope</th>
<th>Drainageway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation, m</td>
<td>71.33</td>
<td>70.53</td>
<td>69.49</td>
</tr>
<tr>
<td>Planimetric curvature</td>
<td>0.01</td>
<td>-0.01</td>
<td>-0.08</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>0.02</td>
<td>0.02</td>
<td>-0.09</td>
</tr>
<tr>
<td>Slope, %</td>
<td>0.60</td>
<td>3.33</td>
<td>1.33</td>
</tr>
<tr>
<td>Flow accumulation</td>
<td>5.01</td>
<td>7.13</td>
<td>30.35</td>
</tr>
<tr>
<td>SHWT, cm</td>
<td>145.83</td>
<td>108.33</td>
<td>75.00</td>
</tr>
<tr>
<td>Sand, %</td>
<td>56.78</td>
<td>54.32</td>
<td>63.75</td>
</tr>
<tr>
<td>Silt, %</td>
<td>24.44</td>
<td>25.50</td>
<td>25.20</td>
</tr>
<tr>
<td>Clay, %</td>
<td>18.79</td>
<td>21.12</td>
<td>11.06</td>
</tr>
</tbody>
</table>

1Surface 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 CH₄ flux determination were seasonally collected between Spring 2004 and Winter 2006, but only Spring 2004 fluxes are reported because of gas chromatography CH₄ channel failure in subsequent seasons. There were no significant differences in CH₄ fluxes between soil management treatments and landscape positions (Fig. 2). On summit landscape position, CTM had an average of 8 mg CH₄-C ha⁻¹ h⁻¹, whereas CsTM had an average flux rate of 310 mg CH₄-C ha⁻¹ h⁻¹. Methane fluxes in the drainageway were 46, 251, 59, and 185 mg CH₄-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 N₂O 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 N₂O fluxes than CT treatment. Dairy manure decreased N₂O flux on CsT treatments (CsT and CsTM). In both seasons, terrain attribute effects on N₂O fluxes varied with soil management (Table 3). In Spring 2004, slope had a negative effect on N₂O flux on CTM treatments. Surface horizon clay content explained 71% (R² = 0.709) of N₂O flux variability on CTM treatments. Soil management interacted with landscape position (P = 0.037) to affect N₂O-N fluxes. Significant soil management treatment differences in N₂O-N flux were observed only in the drainageway (Fig. 3). Averaged across soil management treatments and seasons, average N₂O-N flux in the drainageway was 346 mg ha⁻¹ h⁻¹ N₂O-N relative to 158 and 220 mg ha⁻¹ h⁻¹ N₂O-N on the summit and sideslope, respectively. Within the drainageway, no N₂O-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 N₂O flux, although it had no significant effect on CsT system fluxes.

A significant season by landscape position interaction (P = 0.002) indicated that N₂O 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.

**TABLE 3. Stepwise Regression Relating Landscape Variability Factors to N₂O Flux**

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Independent Variable</th>
<th>Partial R²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 2004</td>
<td>CT</td>
<td>Sand (+)</td>
<td>0.393</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>CTM</td>
<td>Slope (—)</td>
<td>0.459</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td>CsT</td>
<td>SHWT (+)</td>
<td>0.478</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>CsTM</td>
<td>SHWT (—)</td>
<td>0.559</td>
<td>0.021</td>
</tr>
<tr>
<td>Fall 2005</td>
<td>CT</td>
<td>CTI (+)</td>
<td>0.485</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>CTM</td>
<td>Clay (—)</td>
<td>0.709</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>CsT</td>
<td>None</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>CsTM</td>
<td>Profile curvature (+)</td>
<td>0.295</td>
<td>0.131</td>
</tr>
</tbody>
</table>

Only variables with the highest significant contribution to flux variability in each soil management treatment are shown. A positive sign (+) indicates an increase in the given variable causes an increase in N₂O flux, whereas a negative (—) sign indicates the opposite.

¹SHWT: seasonal high water table; CTI: compound topographic index; sand, surface horizon sand content; clay, surface horizon clay content.
²Not significant at ≤0.15.

**Carbon Dioxide Emission**

Season and soil management interacted to alter CO₂ emission (P = 0.001). Significantly different CO₂ emissions were observed in Winter 2005, when CsT treatments had higher emission (1304 g ha⁻¹ h⁻¹ CO₂-C) than CT treatments (227 g ha⁻¹ h⁻¹ CO₂-C). A similar trend was observed in Winter 2006 when CsT treatments had higher emission (1304 g ha⁻¹ h⁻¹ CO₂-C) than CT treatments (227 g ha⁻¹ h⁻¹ CO₂-C). A similar trend was observed in Winter 2006 when CsT treatments had higher emission (1304 g ha⁻¹ h⁻¹ CO₂-C) than CT treatments (227 g ha⁻¹ h⁻¹ CO₂-C). A similar trend was observed in Winter 2006 when CsT treatments had higher emission (1304 g ha⁻¹ h⁻¹ CO₂-C) than CT treatments (227 g ha⁻¹ h⁻¹ CO₂-C). A similar trend was observed in Winter 2006 when CsT treatments had higher emission (1304 g ha⁻¹ h⁻¹ CO₂-C) than CT treatments (227 g ha⁻¹ h⁻¹ CO₂-C).

Effect of landscape variability on winter CO₂ emission varied among soil managements (Table 4). On CT treatments, CO₂ emission was positively influenced by factors that favor increased soil moisture. Flow accumulation increased CO₂ emissions, whereas slope had a negative effect on CO₂ emissions. Lowest slopes were found in the drainageway landscape position that also had higher soil moisture. Whereas higher slope favored CO₂ emissions on CsT treatments in Winter 2006, it also negatively influenced emissions on CsT treatments in the same season. In Winter 2005, surface horizon
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 CH₄ consumption by minimizing soil disturbance that is favorable to CH₄-oxidizing bacteria (Hütsch, 1997), CT did not reduce CH₄ consumption significantly compared with CsT treatments in our study. Hütsch (1997) found that sieving intact soil cores (5 mm) reduced CH₄ oxidation by 57% and 15% on sandy and loamy soils, respectively. Lower CH₄ 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 CH₄ 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.

**Soil Variables**

There were significant season by landscape position by soil management interactions for soil NH₄-N (P = 0.001). Summit and sideslope landscape positions had similar but higher soil NH₄-N in CT treatments in most seasons (Fig. 5) compared with other tillage treatments. However, CT treatments had lower NH₄-N within the drainageway landscape position. Dairy manure tended to decrease NH₄-N in most seasons within summit and sideslope landscape positions, but not on the drainageway.

**TABLE 4. Stepwise Regression Relating Landscape Variability Factors to CO₂ Flux**

<table>
<thead>
<tr>
<th>Season</th>
<th>Management Treatment</th>
<th>Independent Variable¹</th>
<th>Partial R²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter 2005</td>
<td>CT</td>
<td>Flow accumulation (+)</td>
<td>0.710</td>
<td>0.004</td>
</tr>
<tr>
<td>CT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTM</td>
<td>Sand (+)</td>
<td></td>
<td>0.834</td>
<td>0.001</td>
</tr>
<tr>
<td>CsT</td>
<td>Clay (−)</td>
<td></td>
<td>0.400</td>
<td>0.070</td>
</tr>
<tr>
<td>CsTM</td>
<td>None</td>
<td></td>
<td>NS²</td>
<td></td>
</tr>
<tr>
<td>Winter 2006</td>
<td>CT</td>
<td>Slope (−)</td>
<td>0.286</td>
<td>0.138</td>
</tr>
<tr>
<td>CT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTM</td>
<td>Silt (+)</td>
<td></td>
<td>0.370</td>
<td>0.083</td>
</tr>
<tr>
<td>CsT</td>
<td>Slope (−)</td>
<td></td>
<td>0.276</td>
<td>0.147</td>
</tr>
<tr>
<td>CsTM</td>
<td>Slope (+)</td>
<td></td>
<td>0.375</td>
<td>0.080</td>
</tr>
</tbody>
</table>

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 CO₂ flux, whereas a negative (−) sign indicates the opposite.

¹Sand, surface horizon sand content; clay, surface horizon clay content; silt, surface horizon silt content.

²Not significant at ≤0.15.
Other factors, such as soil moisture and temperature, influence CH₄ 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 CH₄ flux differences in the two systems.

FIG. 5. Soil NH₄-N seasonal variation as affected by landscape position and soil management. Bars represent SEM.

FIG. 6. Seasonal total soil N after 6 years of soil management. Data are averaged across soil management treatments. 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 CsT 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$_2$O-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$_2$O measured was mainly a result of NH$_4^+$ nitrification. During the two seasons, N$_2$O fluxes were influenced by soil NH$_4^+$, as indicated by the similarity between N$_2$O flux (Fig. 3) and soil NH$_4$ trends (Fig. 5). Similarly, Breuer et al. (2002) found a positive correlation between nitrification and N$_2$O emission, and negative correlation between nitrification and increasing rates of water-filled porosity.

Lack of a significant tillage effect on N$_2$O 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$_2$O flux on CsT
compared with CT in Fall 2005 may be related to the relatively higher NH4 and NO3-N on these treatments compared with CT treatments in this season. Nitrous oxide is a product of NH4 nitrification and denitrification of NO3 (Meixner and Eugster, 1999). Both processes are controlled by oxygen concentration, but McSwiney et al. (2001) pointed out that high N2O 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 N2O is reduced to N2. Low N2O 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 N2O 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 N2O fluxes were observed within the drainageway, landscape variability effects on N2O flux were not consistent. A positive relationship between surface horizon sand content (Table 3) and N2O fluxes on CT treatments in Spring 2004 is consistent with a negative correlation between N2O 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 N2O flux variance on CSTM or CTM treatments. High surface horizon clay content resulted in decreased N2O fluxes on CSTM treatments, perhaps because of its positive influence on soil moisture. Variation in effect of terrain attributes on N2O 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 CO2 emission under CSTM 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), CO2 flux is a function of CO2 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 CO2 release) would be expected. As expected, CO2 fluxes were lowest in winter (on conventional tillage systems) and may be associated with low winter soil temperatures. Low CO2 fluxes observed in Summer 2004 may be related to noticeably low soil moisture (Fig. 7A) and high soil and air temperatures (data not shown).

Higher N2O fluxes from CT treatments on drainageway landscape positions suggest that N2O 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 (Moser et al., 1998) should be encouraged.

### CONCLUSIONS

Greenhouse gas emissions showed seasonal variations across soil management treatments with higher CO2 emissions from CSTM than CT treatments. This suggests that although cover crops improve soil properties and increase soil nutrients, they may also increase CO2 emissions during the winter season.


