Tillage and Field Scale Controls on Greenhouse Gas Emissions

Juhwan Lee,* Johan Six, Amy P. King, Chris van Kessel, and Dennis E. Rolston

ABSTRACT

There is a lack of understanding of how associations among soil properties and management-induced changes control the variability of greenhouse gas (GHG) emissions from soil. We performed a laboratory investigation to quantify relationships between GHG emissions and soil indicators in an irrigated agricultural field under standard tillage (ST) and a field recently converted (2 yr) to no-tillage (NT). Soil cores (15-cm depth) were incubated at 25°C at field moisture content and 75% water holding capacity. Principal component analysis (PCA) identified that most of the variation of the measured soil properties was related to differences in soil C and N and soil water conditions under ST, but soil texture and bulk density under NT. This trend became more apparent after irrigation. However, principal component regression (PCR) suggested that soil physical properties or total C and N were less important in controlling GHG emissions across tillage systems. The CO₂ flux was more strongly determined by microbial biomass under ST and inorganic N content under NT than soil physical properties. Similarly, N₂O and CH₄ fluxes were predominantly controlled by NO₃⁻ content and labile C and N availability in both ST and NT soils at field moisture content, and NH₄⁺ content after irrigation. Our study indicates that the field-scale variability of GHG emissions is controlled primarily by biochemical parameters rather than physical parameters. Differences in the availability and type of C and N sources for microbial activity as affected by tillage and irrigation develop different levels and combinations of field-scale controls on GHG emissions.

AGRICULTURE is an important anthropogenic source of atmospheric CO₂, N₂O, and CH₄. The net emissions of these greenhouse gases (GHGs) from agriculture account for approximately 20% of the annual increase in radiative forcing of climate change (Cole et al., 1997). Although relative forcing by CO₂ emissions from agriculture is currently considered minor compared to other anthropogenic sources (e.g., fossil fuel combustion and land-use change) (USEPA, 2002), the historical increase in atmospheric CO₂ attributable to long-term cultivation has contributed significantly to the observed global warming over the last 50 yr at the regional and global levels (Intergovernmental Panel on Climate Change, 2001). Globally, organic C in the upper 1 m of agricultural soils is estimated to be about 167 Pg C, which represents approximately 75% of the soil organic C pool in these soils under native vegetation (Cole et al., 1997). These soils have already lost 30 to 70% of their original soil organic C storage in the upper 30 cm due to cultivation, resulting in significant past CO₂ ad-

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Abbreviations: GHG, greenhouse gas; GWP, global warming potential; MBC, microbial biomass carbon; NT, no-tillage; PC, principal component; PCA, principal component analysis; PCR, principal component regression; POM, particulate organic matter; SOM, soil organic matter; ST, standard tillage; WFPS, water-filled pore space; WHC, water holding capacity.
GHG emissions (Eve et al., 2002). Moreover, the turnover rate of SOM tends to be accelerated with increasing temperature, and soil respiration is not limited by the lack of water due to irrigation during the dry summer (Cole et al., 1993; Smith et al., 2003). Eve et al. (2002) showed a lower mitigation potential of NT in California compared to the Great Plains and Corn Belt Regions. However, the potential of GHG reduction with NT is still highly uncertain, and empirical data on GHG emissions from irrigated fields under NT is scarce for Mediterranean climate zones. Therefore, the objectives of this study were to (i) identify the biotic and abiotic factors responsible for the spatial variability of GHG emissions and (ii) determine how the singular and interactive effects of soil properties, tillage, and irrigation practices control GHG emissions.

MATERIALS AND METHODS

Soil Sampling

In 2003, an experimental site was established on a laser-leveled, furrow-irrigated agricultural field of 30 ha (38°36′ N, 121°50′ W) near Davis, Yolo County, California (Fig. 1). The site has a mean annual temperature of 16.1°C and 477 mm precipitation. At the site, three soil types occur: Myers clay (fine, montmorillonitic, thermic Entic Chromoxererts), Hillgate loam (fine, montmorillonitic, thermic Typic Palexeralfs), and San Ysidro loam (fine, montmorillonitic, thermic Typic Palexeralfs) (Soil Conservation Service, 1972). Standard tillage (ST) operations had been applied to the site through fall 2001. Following a spring 2002 maize crop (Zea mays L.), it was put under winter wheat (Triticum aestivum L.) production and converted to NT in fall 2002. In October 2003, the site was split into two fields, and full tillage operations were performed on the north field. These consisted of one pass each of deep ripping, stubble disking, disking to 15 cm, grading, and listing beds. No tillage or mowing was performed on the south field. The fields remained fallow until maize planting in April 2004.

Soil samples were taken at 20 GPS referenced locations, separated by 9 or 18 m from each other, along each of two transects immediately after maize was planted and 56 kg N ha⁻¹ in the form of UAN-32 (urea-ammonium nitrate solution, 32-0-0) was applied in April 2004. The two north–south transects are approximately 450 m apart. At each location, two adjacent intact soil cores (15 cm deep, 4.7-cm diameter) were sampled, and stored at 4°C overnight. One set was analyzed for initial soil properties: total, microbial, and particulate organic matter (POM) fraction C and N as well as soil texture, bulk density, water content, and NH₄⁺ and NO₃⁻ contents. The other set was used for laboratory incubations to measure potential CO₂, N₂O, and CH₄ fluxes.

Soil Analysis

Microbial biomass carbon (MBC) was determined on one set of soil cores before the initiation of the incubation and on another set at the end of the incubation by the fumigation–extraction method, as adapted from Lovell et al. (1995). Briefly, duplicate samples of moist soil (25–30 g) were weighed into plastic containers. The first set of each pair was extracted by shaking for 1 h with 0.1 M K₂SO₄ (100 mL) on a reciprocal shaker, and the suspension was filtered through no. 2 filter paper (Whatman, Brentford, UK) for initial total organic carbon (TOC) and inorganic N (NH₄⁺ –N and NO₃⁻ –N) determination. The second set of samples was exposed to ethanol-free chloroform in a desiccator for 3 d and extracted with 0.1 M K₂SO₄. To determine the amount of microbial C, organic C content in the extracts was measured on a Phoenix 8000 UV-persulfate TOC analyzer (Teledyne Tekmar, Mason, OH). The MBC content was calculated as described by Vance et al. (1987): MBC (µg microbial C g⁻¹ dry soil) = 2.64 (C in fumigated soil – C in unfumigated soil). The concentrations of inorganic N at the onset of the incubation were determined colorimetrically, as described by Forster (1995) for NH₄⁺ and Doane and Horwath (2003) for NO₃⁻. The absorbency of the samples for NH₄⁺ and NO₃⁻ was read at 650 and 540 nm, respectively, against a reagent blank, using a UV-VIS spectrophotometer (UV Mini 1240; Shimadzu, Kyoto, Japan).

After the MBC measurements, the soils were air-dried, mechanically crushed, and sieved through a 2-mm sieve. Crop residues were removed from the samples, and the rock fraction was separated and weighed for bulk density and field water content measurements. Soil water holding capacity (WHC) was determined according to Cassel and Nielsen (1986). Briefly, the moist soil was oven-dried overnight at 105°C without mechanical grinding, weighed, and placed on a funnel with filter paper (no. 2; Whatman). Distilled water was added to the soil until it became completely saturated. Saturated soil was weighed, oven-dried overnight at 105°C, and weighed again. Water-filled pore space (WFPS), the fraction of pore space...
filled with water, of each core at 75% WHC was estimated from gravimetric water content, bulk density, and porosity (mineral density was taken as 2.65 g cm$^{-3}$). Soil texture was determined by the laser diffraction method using an LS-230 with a 750-nm laser beam (Beckman-Coulter, Fullerton, CA) (Eshel et al., 2004).

The soils were also analyzed for total soil C and N, and C and N associated with the POM fraction (53–2000 μm). For separation of POM and sand fractions, air-dried soil (30 g) was mixed with distilled water (150 mL) and agitated by shaking for 1 h. The dispersed suspension was sieved through a 1-mm-thick nylon screen and then filtered through 53-μm-thick nylon screen. The fraction was oven-dried overnight at 50°C, weighed, ground, and stored at room temperature. Organic C and N content in the bulk soil and POM were measured with C/N Analyzer (Carlo Erba, Milan, Italy).

**Measurements of Greenhouse Gas Fluxes**

One set of intact soil cores at field moisture content were placed into approximately 2-L Mason jars sealed with air-tight lids and incubated at 25°C in the dark. At Days 1, 2, 3, 5, 7, and 10 following initiation of the incubation, the jars were connected via Tygon tubing to a Photoacoustic Multi-gas Monitor 1312 (Innova AirTech Instruments, Ballerup, Denmark). The headspace concentrations of CO$_2$, N$_2$O, and CH$_4$ were simultaneously measured at 0, 1, 2, 3, 4, and 5 min, and averaged. As a control, the laboratory ambient concentrations of the three GHGs were measured every minute for 30 min before the initiation of measurements. After each measurement, the jars were opened and aerated for 10 min. When necessary, distilled water was added to the soil core to compensate for loss of water during the incubation based on previously measured soil water contents. After the 10-d incubation at field moisture content, all the cores were adjusted to approximately 75% soil WHC to simulate an irrigation event, and the concentration of the gases was measured again using the same time intervals.

We assumed that the gas concentration inside the Mason jar steadily increased for CO$_2$ and N$_2$O or decreased for CH$_4$ with time, and then the gas flux was calculated from the equation described by Ginting et al. (2003):

$$F = \frac{kA}{T} \left( \frac{V}{A} \right) \left( \frac{dc}{d\tau} \right)$$

where $F$ is the rate of gas accumulation (μg g$^{-1}$ dry soil d$^{-1}$), $k$ is unit conversion, $d$ is gas density (g cm$^{-3}$) at 273 K and 1 atm, $T$ is the air temperature (K) within the Mason jar, $V$ is the volume of air within the mason jar (cm$^3$), and $\left( \frac{dc}{d\tau} \right)$ is the average rate of change of gas concentration (ppm [v/v]) over time (min). Specifically, we assumed no uptake mechanisms (e.g., photosynthesis) for CO$_2$ accumulated during the incubation because all weedy plants were removed from the cores before the onset of the incubation. Thus, CO$_2$ flux represented CO$_2$ production rates. While measuring N$_2$O flux, it was practically impossible to quantify the relative contribution of production versus consumption, including diffusion, to N$_2$O accumulated in the headspace. Therefore, we defined N$_2$O flux as a net difference between production and consumption of N$_2$O over time. Since CH$_4$ production via the anaerobic degradation of organic material is strictly inhibited under aerobic conditions, all agricultural soils take up CH$_4$ via oxidation by methanotrophic bacteria except for flooded or poorly drained sites (Conrad, 1996). Thus, CH$_4$ flux was considered to represent the balance between consumption and production processes of CH$_4$. Additionally, the cumulative amount of GHGs during the 10-d incubation was presented on a 100-yr global warming potential (GWP) weighted basis to compare the relative contribution of each gas to the impacts of net GHG emissions on global radiative forcing by tillage and irrigation. To calculate GWP in CO$_2$ equivalents g$^{-1}$ soil d$^{-1}$ over a 100-yr time horizon, we used conversion factors that 1 μg N$_2$O and CH$_4$ are equivalent to 296 and 23 μg CO$_2$, respectively (Intergovernmental Panel on Climate Change, 2001).

**Statistical Analysis**

Descriptive statistics were collected and correlation coefficients were calculated between all measured GHG and soil properties using PROC CORR in SAS (SAS Institute, 2004). Normality and log-normality of the residuals of the original data were checked. Due to the unreplicated nature of the tillage treatments, only descriptive statistics were used to compare results between ST and NT. Soil properties were assumed to be spatially autocorrelated within each field managed under NT versus ST. Therefore, if any two properties were significantly correlated at the 5% significance level, the significance of correlation was rechecked by accounting for autocorrelation through the use of a modified $r$ test (Clifford et al., 1989).

When many variables have been input into a regression model, multicollinearity occurs due to a strong correlation among several variables, often leading to biased and inflated model predictions. Therefore, the principal component regression (PCR) method was performed to eliminate multicollinearity problems among soil properties for quantifying the relationships of GHG fluxes and soil properties in tillage systems. First, variance inflation factors (VIF) were used to determine which variables may cause multicollinearity (Rawlings et al., 1998). The VIF value for any variable was calculated as described by Freund and Littell (2000):

$$VIF = \frac{1}{1 - R_i^2}$$

where $R_i^2$ is the coefficient of determination for the regression of the $i$th independent variable on all other variables. Second, to analyze the structure of correlations among soil properties, principal component analysis (PCA) on the soil variables was performed using PROC PRINCOMP in SAS (Freund and Littell, 2000; SAS Institute, 2004). Principal component analysis created principal components (PCs) as a new set of variables that were uncorrelated. To eliminate PCs that were not making a considerable contribution to the regression and causing multicollinearity, only PCs with eigenvalues $> 0.1$ and a condition index $< 30$ were retained for the regression analysis (Freund and Littell, 2000). Subsequently, PROC REG was used to perform PCR with the scores of the extracted PCs as independent variables and CO$_2$, N$_2$O, and CH$_4$ fluxes as dependent variables, respectively. In regression models, PC selection was based on adjusted $r^2$ and Mallows C(P) statistics (Mallows, 1973). Therefore, the stepwise model included the least possible number of PCs. Finally, the regression coefficients for the PCs selected in the model were converted to the regression coefficients for original soil variables to compare the relative importance of the soil properties on each of the GHG fluxes (Rawlings et al., 1998).

**RESULTS AND DISCUSSION**

The spatial variability of GHG emissions from agriculture strongly depends on complex associations among soil physical, chemical, and biological properties.
combined with the interactive impacts of management-induced changes. Therefore, understanding the nature of associations among controlling factors before and after the implementation of NT is also key in evaluating the mitigation potential of NT relative to ST in irrigated agroecosystems. It is, therefore, crucial to deal with the uncertainty in the emission estimates when analyzing the underlying relationships between GHG emissions and soil properties, which vary across systems under different management practices. However, this requires considering multicollinearity caused by strong intercorrelation among controlling soil factors, which can result in biased relationships in space (Ping et al., 2004; Rawlings et al., 1998).

Spatial Variability of Greenhouse Gas Emissions and Soil Properties by Tillage and Irrigation

At field moisture content, NH$_4^+$ and the POM associated C and N had the largest spatial variability in both treatments, with coefficient of variation (CV) values ranging from 71 to 81% (Table 1). Microbial C and NO$_3^-$ also had considerable variability (CV = 46–51%). Except for sand content (CV = 23–24%), water content (CV = 18–21%), and WFPS (CV = 29–37%) with moderate variability, the measured soil physical properties had relatively lower spatial variability (CV = 10%) compared to the measured chemical and biological properties of the soil. The results indicate that these chemical and biological properties can be highly variable at the landscape scale (Pennock et al., 1994; Yanai et al., 2003) and are more sensitive to soil disturbance associated with a change from ST to NT or vice versa and irrigation compared to the physical properties (Pankhurst et al., 2002). As water content and WFPS increased, the concentrations of MBC, NH$_4^+$, and NO$_3^-$ in the soil greatly increased but the spatial variation decreased in both treatments. This indicates that the changes in these chemical and biological properties were closely related to the spatial variation of soil water, while the other physical properties remained constant. Similarly, Rey Benayas et al. (2004) found that chemical properties, especially total ion content and soil acidity, were directly controlled by soil water at field scales in Mediterranean montane meadows. In contrast to the change with water content, in our study there was no major increase or decline in the chemical and biological properties by the short-term impacts of a change from NT to ST. A similar trend was also found at 75% WHC. Since POM-C and -N contents were not directly quantified at 75% WHC, the combined effects of tillage and irrigation treatments on POM-C and -N were not determined.

Since the spatial variability of GHG emissions was large at the field scale, no differences in the CO$_2$, N$_2$O, and CH$_4$ emissions between tillage treatments were found under field moisture conditions (Fig. 2 and 3). Both CO$_2$ and N$_2$O emissions were slightly greater in ST than in NT at field moisture content. At field moisture content, the average values of the CO$_2$ and N$_2$O fluxes ranged from 5.67 to 10.99 µg C g$^{-1}$ d$^{-1}$ and 0.001 to 0.005 µg N g$^{-1}$ d$^{-1}$ in ST, and 5.39 to 8.73 µg C g$^{-1}$ d$^{-1}$ and 0.001 to 0.003 µg N g$^{-1}$ d$^{-1}$ in NT, respectively (Fig. 3). Upon wetting the soil cores to 75% WHC, CO$_2$ and N$_2$O emissions peaked immediately, but to a greater degree in the NT than ST soils, and then gradually decreased over time to the emission levels at field moisture content. Tillage-induced differences in emissions were observed when soil water content was increased. Upon adding water, cumulative CO$_2$ emissions over the 10-d incubation increased 1.2 times in ST and 2 times in NT, respectively (Fig. 2). Moreover, cumulative N$_2$O emissions increased 2.5 times in ST and 5.7 times in NT at 75% WHC compared to field moisture content. This indicates that irrigation had a greater impact on N$_2$O than CO$_2$ emissions in both ST and NT soils. However, the range and average values of water content and WFPS were similar for both ST and NT soils (Table 1). Therefore, the differences in emissions were likely caused by the differences in other soil properties, which were closely linked to varying soil water conditions combined with tillage.

Emissions of CH$_4$ were negative at field moisture content, indicating that the soil was a small sink for atmospheric CH$_4$. Soil capacity to take up CH$_4$ tended to

Table 1. Descriptive statistics of measured soil properties. Numbers following the solidus are the values of soil variables at 75% water holding capacity.

<table>
<thead>
<tr>
<th>Property†</th>
<th>Standard tillage</th>
<th>No-tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ‡</td>
<td>Minimum</td>
</tr>
<tr>
<td>Sand, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total C, g C m$^{-2}$</td>
<td>1597</td>
<td>1233</td>
</tr>
<tr>
<td>Total N, g N m$^{-2}$</td>
<td>163</td>
<td>134</td>
</tr>
<tr>
<td>POM-C, g C kg$^{-1}$ POM</td>
<td>65.2</td>
<td>16.9</td>
</tr>
<tr>
<td>POM-N, g N kg$^{-1}$ POM</td>
<td>3.14</td>
<td>1.01</td>
</tr>
<tr>
<td>NH$_4^+$, µg N g$^{-1}$</td>
<td>2.81/15.62</td>
<td>0.43/5.88</td>
</tr>
<tr>
<td>NO$_3^-$, µg N g$^{-1}$</td>
<td>4.34/6.06</td>
<td>1.70/15.0</td>
</tr>
<tr>
<td>MBC, µg C g$^{-1}$</td>
<td>117.6/68.1</td>
<td>42.98/3.5</td>
</tr>
<tr>
<td>Bulk density, g cm$^{-3}$</td>
<td>1.09/1.12</td>
<td>0.92/0.93</td>
</tr>
<tr>
<td>Water content, cm$^{-3}$</td>
<td>0.16/0.30</td>
<td>0.11/0.22</td>
</tr>
<tr>
<td>WFPS, ‰</td>
<td>33.5/33.5</td>
<td>19.4/34.9</td>
</tr>
</tbody>
</table>

† POM-C and -N, particulate organic matter associated carbon and nitrogen; MBC, microbial biomass carbon; WFPS, water-filled pore space.
‡ Coefficient of variation.
be higher in ST than NT. Consumption rates of CH$_4$ in ST increased 2.5 times at 75% WHC compared to field moisture content. In contrast, the NT soil became a source for CH$_4$, indicating greater anaerobic activity as soils reached a point where O$_2$ availability could be relatively limited (Aon et al., 2001). This also suggests that the NT soil could potentially become a short-term source for CH$_4$ after an irrigation event.

To compare radiative forcing from net GHG emissions under different combinations of tillage and irrigation, global warming potential (GWP) over a 100-yr time horizon was calculated from the cumulative emission of the individual GHGs over the 10 d of the incubation (Intergovernmental Panel on Climate Change, 2001) (Table 2). The CO$_2$ emissions were the greatest contributor to the GWP of both the ST and NT soils at field moisture content. The GWP was on average greater in the ST than NT soils, but the tillage-induced difference in the GWP was not clear due to spatial variation among soils. However, increased CO$_2$ and N$_2$O emissions contributed more to the GWP budgets in the NT than ST cores at 75% WHC, resulting in a greater average GWP for the NT than ST soils after water application. This indicates the interactive effects of tillage and irrigation on GHG fluxes. Thus, increasing soil water content through irrigation in NT potentially counterbalances its limited CO$_2$ mitigation potential compared to ST. Although CO$_2$ was still the dominant GHG on wetting in both tillage treatments, N$_2$O flux increased more than CO$_2$ flux; the GWP from the emissions of CH$_4$ was almost negligible.

Fig. 2. Temporal changes in the cumulative amount of greenhouse gas fluxes at field moisture and 75% water holding capacity (WHC) conditions (n = 20 for each treatment). Arrow indicates when samples were brought up to 75% WHC. Bars indicate the standard error of the mean. ST, standard tillage; NT, no-tillage.

Fig. 3. Temporal changes in CO$_2$ production rates, net N$_2$O emission rates, and CH$_4$ consumption rates at field moisture and 75% water holding capacity (WHC) conditions (n = 20 for each treatment). Arrow indicates when samples were brought up to 75% WHC. Bars indicate the standard error of the mean. ST, standard tillage; NT, no-tillage.
Table 2. Global warming potential of cumulative greenhouse gases over 10 d of the incubation at field moisture content and 75% water holding capacity. Numbers in parentheses indicate the standard error of the mean.

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard tillage</th>
<th>No-tillage</th>
<th>µg CO₂ equivalent kg⁻¹ soil per d⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>247.0 (19.3)</td>
<td>298.4 (18.7)</td>
<td>237.1 (21.5) 476.3 (29.8)</td>
</tr>
<tr>
<td>N₂O</td>
<td>9.19 (2.44)</td>
<td>23.3 (3.23)</td>
<td>6.52 (2.37) 36.9 (5.95)</td>
</tr>
<tr>
<td>CH₄</td>
<td>-0.29 (0.23)</td>
<td>-1.13 (0.31)</td>
<td>-0.58 (0.14) 0.19 (0.19)</td>
</tr>
<tr>
<td>Total</td>
<td>255.9 (20.3)</td>
<td>320.6 (19.7)</td>
<td>243.1 (23.3) 513.4 (31.3)</td>
</tr>
</tbody>
</table>

Correlation Analysis between Greenhouse Gas Emissions and Soil Properties by Tillage and Irrigation

There was clearly a difference in relationships between GHG and soil properties under different tillage and irrigation treatments (Table 3).

Carbon Dioxide Emissions

Emissions of CO₂ from NT soils were significantly correlated to water content, WFPS, and inorganic N content at field moisture content, while no correlations with soil properties were found in ST. Lack of significant correlations between CO₂ and measured soil properties in ST at field moisture content is likely because the interacting spatial patterns of controlling properties were highly confounded after tillage. However, cumulative CO₂ emissions were significantly correlated with soil texture in both ST and NT at 75% WHC. This indicates that CO₂ emissions were strongly controlled by continuous changes in soil water regardless of tillage (Reicosky et al., 1999), and that soil texture was predominantly important in regulating CO₂ emissions, as the spatial variation of other controlling properties associated with soil water conditions tended to decrease after an irrigation event. For example, both water and WFPS had significant impacts on CO₂ and N₂O emissions at field moisture content under NT, suggesting that SOM mineralization was initially limited by lack of water (Davidson et al., 2000; Reicosky et al., 1999) and air–water balance in the soil, thereby O₂ diffusion and availability (Balesdent et al., 2000). However, irrigation tended to result in less significant correlation between GHG emissions and soil water conditions (i.e., gravimetric water content and WFPS) in NT as microbial activity was not limited by water (Mosier et al., 2003). In addition, MBC and bulk density were most significantly correlated to increased CO₂ emissions in ST at 75% WHC, suggesting enhanced microbial responses due to irrigation (Reicosky et al., 1999), and total C and N were negatively correlated to cumulative CO₂ emissions during the incubation. In NT, CO₂ emissions were significantly correlated to NO₃⁻ and/or NH₄⁺ contents, which

Table 3. Significant (P < 0.05) Pearson’s correlation coefficients of greenhouse gases and soil properties by tillage and irrigation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard tillage</th>
<th>No-tillage</th>
<th>Cumulative§</th>
<th>Flux§</th>
<th>75% water holding capacity (WHC)</th>
<th>Cumulative</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td></td>
<td>-0.45</td>
<td>0.47</td>
<td>0.73</td>
<td>-0.49</td>
<td>0.70</td>
</tr>
<tr>
<td>Clay</td>
<td>0.55</td>
<td></td>
<td>0.49</td>
<td>-0.86</td>
<td>0.63</td>
<td>-0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>Silt</td>
<td></td>
<td></td>
<td>-0.52</td>
<td>-0.55</td>
<td>0.54</td>
<td>-0.51</td>
<td>-0.54</td>
</tr>
<tr>
<td>Total C</td>
<td>0.75</td>
<td>0.74</td>
<td>-0.52</td>
<td>-0.54</td>
<td>-0.46</td>
<td>-0.51</td>
<td>-0.54</td>
</tr>
<tr>
<td>Total N</td>
<td>0.73</td>
<td>0.69</td>
<td>-0.50</td>
<td>-0.54</td>
<td>-0.46</td>
<td>-0.51</td>
<td>-0.54</td>
</tr>
<tr>
<td>MBC</td>
<td></td>
<td></td>
<td>0.74</td>
<td>0.49</td>
<td>0.78</td>
<td>0.74</td>
<td>0.59</td>
</tr>
<tr>
<td>BD</td>
<td></td>
<td></td>
<td>-0.68</td>
<td>0.68</td>
<td>-0.68</td>
<td>-0.57</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td>-0.52</td>
<td>0.50</td>
<td></td>
<td>-0.62</td>
<td>-0.49</td>
</tr>
<tr>
<td>WFPS</td>
<td></td>
<td></td>
<td>-0.62</td>
<td>0.62</td>
<td></td>
<td>-0.62</td>
<td>-0.49</td>
</tr>
</tbody>
</table>

† POM-C and -N, particulate organic matter associated carbon and nitrogen; MBC, microbial biomass carbon; BD, bulk density; WFPS, water-filled pore space.
‡ Cumulative greenhouse gases (GHGs) over 10 d of the incubation at field moisture content and 75% WHC.
¶ GHG fluxes are averages at Day 10 of the incubation at field moisture content and 75% WHC.
§ Global warming potential.
# Not determined.
were correlated to soil water dynamics via irrigation. Therefore, \( \text{CO}_2 \) emissions were enhanced more by increased availability of inorganic N in NT than in ST, suggesting N limitation in NT compared to ST (Hernández-Hernández and López-Hernández, 2002).

### Nitrous Oxide and Methane Emissions

At field moisture content, \( \text{N}_2\text{O} \) emissions were significantly correlated to many soil physical and chemical properties. In particular, emissions of \( \text{N}_2\text{O} \) were significantly correlated to POM-C and -N under ST, whereas total C and \( \text{NH}_4^+ \), and \( \text{NO}_3^- \) were important under NT. This indicates that \( \text{N}_2\text{O} \) flux was directly dependent on POM-C and -N inputs under ST, but on readily available inorganic N sources from total C and N under NT. Differences in availability and type of N sources between tillage systems were presumably affected by differences in residue decomposition via crop residue incorporation and resulting substrate quality (Hu et al., 1997; Wood and Edwards, 1992). Soil texture and MBC became significant in regulating \( \text{N}_2\text{O} \) flux at 75% WHC in ST. However, there were no clear correlations between \( \text{N}_2\text{O} \) emissions and soil physical and chemical properties at 75% WHC under NT, except \( \text{NH}_4^+ \) was significantly correlated to \( \text{N}_2\text{O} \) flux. The results suggest that \( \text{N}_2\text{O} \) emissions were indirectly regulated by water conditions, which primarily controlled a series of microbial processes of soil N transformation (e.g., denitrification) in association with O\(_2\) limitation (Aon et al., 2001; Bollmann and Conrad, 1998). Therefore, \( \text{N}_2\text{O} \) emissions resulted primarily from soil N availability, suggesting strong soil responses to nitrification and denitrification (Barnard and Leadley, 2005). Although \( \text{CH}_4 \) emissions were not correlated to any of the measured soil properties at field moisture content, they were significantly correlated to soil texture regardless of tillage and water content in NT at 75% WHC. This suggests that \( \text{CH}_4 \) flux could be strongly controlled by physical processes between agricultural soils and the atmosphere (Bowden et al., 1998). Global warming potential was also significantly correlated to water content, WFPS, and inorganic N at field moisture content in NT and to soil texture at 75% WHC in both ST and NT. This is mainly because \( \text{CO}_2 \) was the most important GHG to the GWP budget (Table 2).

We found that the field-scale relationships of soil properties with GHG emissions were strongly affected by soil and water management (Table 3). In addition, it was possible to identify a set of soil properties with significant correlations to the emission of \( \text{CO}_2 \) and other trace gases. However, none of these analyses took into consideration the effects of intercorrelation among the soil properties on GHG emissions.

### Principal Component Analysis of the Structure of Correlations among Soil Properties as Related to Greenhouse Gas Emissions

Soil texture, total C and N, and POM-C and -N had VIF values greater than 10 (data not shown). This indicates that they could be more closely related to the other soil variables than to the flux of \( \text{CO}_2 \), \( \text{N}_2\text{O} \), or \( \text{CH}_4 \). Furthermore, soil texture, especially sand content, caused rather severe multicollinearity problems compared to the other soil properties, indicating its strong effects on other physical, chemical, and biological properties of the soil. Bulk density, water content, and WFPS also had relatively large VIF values, indicating the presence of multicollinearity. Only MBC, \( \text{NH}_4^+ \), and \( \text{NO}_3^- \) were not involved in multicollinearity. Since the spatial pattern for these chemical and biological properties varied considerably and was more complex than other soil properties within a field (Yanai et al., 2003), they usually had weak or no correlations with the other properties. Multicollinearity often makes the variances of estimates of regression coefficients unreliably large (Freund and Littell, 2000). Therefore, PCR was performed to eliminate multicollinearity between variables.

The PCA analysis identified eight and six PCs for GHG at field moisture content and 75% WHC, respectively, with eigenvalues greater than 0.1 and condition indices smaller than 30. These PCs may have a meaningful contribution to the overall regression for GHG fluxes because the percentage of total variance by each PC was approximately 5 to 45% in their controlling factors, which can be related to the variation of GHG fluxes at the same spatial scale. The loadings of the first five PCs accounted for approximately 85 to 90% of the total variation of the measured soil variables (Tables 4 and 5).

At field moisture content, most of the variability of the soil variables was explained by differences in total C and N content, water content, WFPS, and to a lesser degree by differences in soil texture, bulk density, and POM-C and -N in ST (Table 4). Thus, PC1 was dominated by the properties controlling the SOM status of the soil, whereas PC2 measured soil structure components as well as the availability of soil C and N. Principal Component 3 was dominated by MBC and to a lesser degree a function of \( \text{NH}_4^+ \) and \( \text{NO}_3^- \). Principal Component 4 was clearly dominated by \( \text{NH}_4^+ \) and also showed a slight contrast between \( \text{NH}_4^+ \) and \( \text{NO}_3^- \). However, major patterns of variability in NT were primarily associated with soil texture (PC1), followed by bulk density (PC2), and to a lesser degree water content, and total C and N (PC3). Water content and WFPS were strongly associated with other soil variables in ST at field moisture content, but there was a much smaller contribution to the total variation from water content or WFPS in NT. This may be due to differences in SOM dynamics via tillage-induced changes in soil structure between ST and NT (Balesdent et al., 2000), which affected the availability of C and N and related microbial activity. Since ST is generally characterized by a faster turnover rate of incorporated crop residues into soils compared to NT (Wood and Edwards, 1992), soil C and N accounted for a significant portion of the variation in ST. In contrast, total and POM-C and -N were less important due to the relatively large contribution of bulk density, and MBC accounted for very little variation in NT. In NT, \( \text{NO}_3^- \) and MBC dominated PC4 and PC5, respectively. Overall, differences in loading between ST and NT indicated an interaction between tillage and inherent soil properties that control GHG emissions.
The trend in loading changes induced by tillage at 75% WHC was generally similar to that at field moisture content (Table 5). However, even though the influence of soil water was larger at 75% WHC, the influences of the other soil properties also increased correspondingly. For example, bulk density dominated PC1 in ST, and total C and N in NT. In addition, soil inorganic N contents influenced more of the variation regardless of tillage. Since SOM mineralization was greatly enhanced with increasing water content (Davidson et al., 2000; Reicosky et al., 1999), availability of inorganic N probably increased.

**Principal Component Regression Analysis of the Relationship between Greenhouse Gas Emissions and Soil Properties**

Models obtained by PCR accounted for approximately 50 to 76% of the observed spatial variability of CO₂ flux, 52 to 79% of N₂O flux, and 43 to 77% of CH₄ flux by tillage and irrigation at a confidence level of 5% (Table 6). Considering the high inherent spatial variability at the field scale used in this study, these models successfully described a set of predominant soil properties controlling GHG fluxes. However, no significant model for CO₂ flux was found in ST at field moisture content due to a lack of significant correlation structure among their controlling variables (Table 3). Even though a confidence level of 0.20 was used (Pennock et al., 1994), no reliable relationships between CO₂ flux and the soil properties were identified in ST at field moisture content.

**Carbon Dioxide Emissions**

In ST, CO₂ flux at 75% WHC was positively related to MBC. Although there was a significant contribution of PC1 to the regression, soil texture (Table 5), soil water, and total C and N did not directly relate to CO₂ flux like MBC. Based on the relative magnitude of the regression coefficients for NH₄⁺ and NO₃⁻, the effect of soil inorganic N contents on CO₂ flux was also not evident. Therefore, field-scale control of CO₂ flux was directly regulated by MBC.

In NT, MBC also had some degree of influence on CO₂ flux but was less meaningful in the regression relative to soil water and inorganic N contents. The CO₂ flux was predominantly regulated by NO₃⁻ along with...
Nitrous Oxide Emissions

Log-transformed N₂O flux was related to POM-C and -N, and NO₃⁻ in ST, and mainly to NO₃⁻ in NT at field moisture content. The predominant control of N₂O flux by NO₃⁻ in ST and NT indicates the relative importance of NO₃⁻ availability under aerobic soil conditions at field moisture content. Compared to field moisture content, the effect of NO₃⁻ on N₂O flux was slightly smaller or negligible at 75% WHC while the NH₄⁺ impact generally increased in both tillage treatments. Even though NH₄⁺ was still not as important in regulating N₂O flux compared to MBC in ST, NH₄⁺ tended to be more important as a key controller of N₂O production in NT as anaerobic soil microbial activity developed after water application. Therefore, N₂O flux was related to a change in NO₃⁻ and NH₄⁺ content, which represents change in soil N transformations following a tillage and irrigation (Mosier et al., 1996). In addition, the strong dependency of N₂O flux on POM-C and -N in ST confirms that N₂O emissions were strongly dependent on labile C and N availability. However, POM-C and -N were less important for N₂O emissions in NT than in ST. Similar to CO₂ flux, this difference between tillage systems is probably due to tillage-induced differences in the rates of incorporation and mineralization of crop residues, and subsequent differences in the availability and type of C and N sources between ST and NT (Hu et al., 1997; Wood and Edwards, 1992). As soil water content increased, N₂O flux was evidently regulated by MBC, and the effect of water content also greatly increased for both ST and NT soils.

In a multivariate context, PCs1–3 and PC6 were associated with the regression for N₂O flux in ST, and PC1 and PC4 in NT. Only PC2 was significantly related to the regression in ST while all selected PCs had significant contributions in NT. However, the effects of main physical and chemical properties were masked due to their multiple associations with other properties and only directly or indirectly linked to soil properties controlling microbial activity. Similar to CO₂ production, this suggests the control of N₂O production in the soil by chemical and biological properties, which were in turn controlled by physical properties. The flux of N₂O in ST was positively related to MBC, whereas it was negatively related to MBC in NT. This is probably due to
changes in microbial activity responsible for the spatial variation of N$_2$O as affected by the difference in the variation of inorganic N contents between tillage systems after water application. Regardless of tillage, N$_2$O flux tended to increase linearly with increasing WFPS values from 20 to 70%, which increases anaerobic zones in the soil, leading to increased denitrification (de Klein and van Logtestijn, 1996). This indicates that the N$_2$O flux was strongly controlled by the variation of soil water conditions. In addition, the pattern of N$_2$O emissions in response to soil water was more variable in the NT soils than the ST soils. This pattern presumably depends on the complexity of soil structure, such as pore size distribution, which probably differed considerably between the ST and NT soils (Franzluebbers et al., 1995).

**Methane Emissions**

The flux of CH$_4$ was mostly characterized by differences in POM-C and -N for the ST and NT soils at field moisture content. In ST, CH$_4$ flux was also correlated to MBC and NO$_3$$^-$$. In ST, the regression for CH$_4$ flux was strongly dominated by PC2, PC3 (Table 4), and PC6 (data not shown). Principal Component 2 measured the simultaneous effects of soil texture and bulk density on CH$_4$ emissions (Table 4), but these physical properties weakly influenced CH$_4$ flux at field moisture content. Principal Component 3 and PC6 showed a contrast of MBC associated with the availability of soil inorganic N, and PC6 had a significant relation with CH$_4$ flux. This suggests that CH$_4$ oxidation is directly controlled by nutrient availability under aerobic conditions (Conrad, 1996). In NT, CH$_4$ flux was significantly correlated to PC3 (Table 4) and PC7 and to a lesser extent to PC8 (data not shown). Principal Component 3 measured soil C and N along with soil water. Principal Component 7 was dominated by POM-C and -N, and PC8 by bulk density. Therefore, CH$_4$ flux in NT was greatly influenced by soil C and N in association with soil water. In general, soil water affects both CH$_4$ production and uptake simultaneously by developing anaerobic conditions and changing its diffusion to the aerobic surface (Mosier et al., 2003; Yamulki and Jarvis, 2002). Accordingly, effects of soil texture on CH$_4$ flux were also found due to the field-scale association between soil texture and soil water (Reny Benayas et al., 2004). The flux of CH$_4$ was apparently influenced by soil texture in both ST and NT soils at 75% WHC. For example, CH$_4$ consumption in both ST and NT soils generally decreased more rapidly for the sandy soils relative to the fine-textured soils at 75% WHC. Conversely, there was an inverse relationship between CH$_4$ consumption and sandy soils or the fine-textured soils in ST at field moisture content, where the range of soil WFPS values (19–54%) were relatively small. Therefore, this change in the sign of regression estimates for soil texture strongly depends on spatial variation in soil water (Mosier et al., 1996). In ST, CH$_4$ flux was much more strongly correlated to NH$_4$$^+$ at 75% WHC compared to field moisture content. This was due to the significant associations of PC2 and PC3 with CH$_4$ flux. Clearly, PC2 and PC3 were dominated by soil texture and NH$_4$$^+$, respectively (Table 5). The negative effect of soil NH$_4$$^+$ on CH$_4$ flux may indicate the inhibition of CH$_4$ oxidation by increased NH$_4$$^+$ in agricultural soils, coupled with water application (Merino et al., 2004). In NT, CH$_4$ flux was significantly related to PC1 and PC2. In general, there were no major differences in dominant controlling factors between ST and NT at 75% WHC except for WFPS. A contrast in bulk density between ST and NT indicates that CH$_4$ oxidation was inversely correlated to soil compaction.

**CONCLUSIONS**

Since the spatial variability of GHG emissions was large at the field scale, there were little or no differences in the emissions between ST and NT. Irrigation apparently increased the differences in GHG emissions, but led to a pattern of emissions by tillage that contrasted with emissions at field soil moisture content. The changes indicate the effect of tillage–irrigation interactions on GHG emissions. Both CO$_2$ and N$_2$O emissions in ST and NT were nearly equivalent at field moisture content. Emissions reached their maximum rates after water application, to a greater degree in the NT than ST soils, and then gradually decreased over time to the emission levels at field moisture content. As a result, limited CO$_2$ mitigation potential after conversion to NT was counterbalanced by the effect of water application (e.g., irrigation).

We identified a set of soil properties with significant relationships to the emission of CO$_2$ and other trace gases by using PCR (PCA along with regression analysis) in ST and NT under combinations of irrigation treatments. Principal component regression effectively eliminated multicollinearity problems, which cause biased relationships with GHG emissions in space. Thus, several soil properties were newly identified as key controlling factors and others were eliminated. Principal component regression revealed that GHG emissions tended to be more strongly related to microbial activity and labile C and N sources than the other soil physical or chemical properties (e.g., soil texture), which dominated most of the variation of controlling factors. This suggests that soil physical properties and total C and N do not much improve predictions of field-scale GHG emissions. In our study, CO$_2$ flux was more strongly regulated by microbial biomass under ST and inorganic N contents under NT than soil physical properties. Similarly, N$_2$O and CH$_4$ fluxes were predominantly controlled by NO$_3$$^-$ content and labile C and N availability (e.g., POM) in both ST and NT soils at field moisture content. After an irrigation event, NH$_4$$^+$ tended to be more important as a key controller of the non-CO$_2$ GHG fluxes as anaerobic soil microbial activity developed. Overall, we found that the field-scale variability of GHG emissions is controlled primarily by chemical and biological parameters and less by physical parameters. Additionally, differences in the availability and type of C and N sources for microbial activity as affected by tillage and irrigation tend to develop different levels and combinations of field-scale control of GHG emissions.
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