Agriculture, Ecosystems and Environment 129 (2009) 378–390

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Tillage and seasonal emissions of CO_2, N_2O and NO across a seed bed and at the field scale in a Mediterranean climate

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ARTICLE INFO

Article history:
Received 4 May 2008
Received in revised form 14 October 2008
Accepted 16 October 2008
Available online 28 November 2008

Keywords:
Mediterranean climate
Agriculture
CO_2
N_2O
NO
Tillage
Crop
Season

ABSTRACT

Whereas the contribution of agriculture to the emissions of greenhouse gases (GHGs) is well known, especially of NO_x gases following the application of N-fertilizer additions, quantitative estimates across fields remain uncertain. Here, we quantified CO_2, N_2O, and NO emissions from an irrigated field under standard tillage and in a field recently converted (≈5 years) to minimum tillage in Yolo County, California, under a Mediterranean climate. We focused on the spatiotemporal variation of GHG emissions among positions across a seed bed and at the field scale. Seasonal CO_2 and N_2O fluxes ranged from 4.6 to 52.4 kg C ha^{-1} day^{-1} and 0 to 23.7 g N ha^{-1} day^{-1}, respectively. There was a significant seasonal pattern of CO_2 emissions as a function of crop growth, while the level of CO_2 flux rates varied annually by crop type and the previous year's soil C inputs. The seasonal N_2O emissions coincided with N fertilization placement and irrigation events. With the exception of immediately after N fertilizing, NO emissions were on average 2–33 times lower than N_2O emissions. Whereas gross effects of tillage and position in the seed bed on CO_2 and N_2O emissions were not significant, the emissions were significantly different in a specific seed bed position because of an interaction between tillage and position in the seed bed. For example, N_2O fluxes in the side dress position were significantly greater than fluxes from other seed bed positions, and were further accentuated by a significant tillage effect. At the field scale, soil-water content and temperature were generally related to both optimum CO_2 and N_2O emissions, but the relationships were highly variable. The results suggest that position-specific variations and interaction with tillage should be accounted for to improve the estimates of GHG emissions from irrigated soils.

1. Introduction

Terrestrial ecosystems are considered potential future sinks of C and could partially offset the increase in atmospheric CO_2 (Smith, 1999). Enhanced C sequestration in soils requires either an increase in primary productivity without an equivalent increase in mineralization of plant residues and soil organic matter (SOM), or a decrease in C mineralization without a commensurate decrease in primary production. As conservation tillage can enhance soil C sequestration, it has the potential to contribute to the mitigation of climate change (Schlesinger, 1999). However, conservation tillage may increase N_2O emissions under certain circumstances, thereby offsetting C sequestration benefits (Smith et al., 2002; Six et al., 2004).

In the agricultural sector of the US, agricultural soil management accounted for almost 94% of total US N_2O emissions from 1990 to 2004 (USEPA, 2006). In 2004, N_2O emissions from soil management activities accounted for 29.7% of the combined emissions of CO_2, N_2O, and CH_4 from the agricultural sector at the national scale (USEPA, 2006). In addition, historical C loss from soils caused by long-term cultivation may be directly linked to the recently observed global warming trend (IPCC, 2007). Consequently, a major challenge for the agricultural sector is to increase soil C sequestration while decreasing N_2O emissions through novel soil management practices.

Several aspects have to be taken into account when an emissions inventory for irrigated soils in a Mediterranean climate is compiled. First, California's Central Valley, the most intensively irrigated agriculture in the US, is characterized by high soil temperatures and moisture for much of the year, leading to inherently fast decomposition rates. Current estimates of SOC accumulation under irrigated conditions are highly variable and

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doi:10.1016/j.agee.2008.10.012

range between 25 and 52 g C m^{-2} $year^{-1}$ (Eve et al., 2002). Furthermore, the interactions between no or minimum tillage and irrigation practices has not been widely investigated. Secondly, raised beds and furrows are typically formed for maintaining reasonable irrigation uniformity. Previous studies showed that biophysical soil properties (e.g., soil N availability) and microclimate had a significant landform pattern across the field (Hook and Burke, 2000; Walley et al., 2002). Similarly, soil properties controlling the rate of decomposition would vary spatially across positions in the middle of the bed, the furrow, between plants, or across the fertilizer band. Accordingly, the spatial variability and intensity of CO_2 and N_2O emissions would likely be position-specific, but has not been investigated. Estimates of agricultural GHG emissions are needed to develop economically efficient as well as effective policies in mitigating and reducing GHG emissions in farming systems (Cole et al., 1997; California Energy Commission, 2005).

In addition, NO is produced in soils via the nitrification and denitrification processes leading to the formation of N_2O. Therefore, N_2O and NO fluxes should be measured simultaneously to better understand net N loss. However, the intensity of NO emissions from agricultural, irrigated soil in a Mediterranean climate remains largely unquantified because NO is usually considered a minor source of N loss from agricultural soils.

Soil-water content and temperature not only exert a large effect on the rate of organic matter decomposition but also on N_2O fluxes (Conen et al., 2000; Drury et al., 2003; Kirschbaum, 1995). For example, Ryden (1981) showed that source or sink activity for atmospheric N_2O was possibly switched by changes in both soil-water content and temperature. Although their effects on emission of soil trace gases are highly variable and complex (Kirschbaum, 1995), both soil-water content and temperature are often sensitive to changes in tillage (Franzluebbers et al., 1995). These soil properties can then be used to improve estimates of field level CO_2 and N_2O emissions from the soil managed under different tillage practices.

The objective of this field study were to (i) quantify CO_2, N_2O, and NO emissions from an irrigated field under standard and minimum tillage, (ii) determine the temporal and spatial variations in CO_2, N_2O, and NO emissions across a seed bed, and (iii) evaluate, at the field scale, the relationships between CO_2 or N_2O emissions and their underlying factors: soil water and temperature.

2. Materials and methods

2.1. Site description

The research site is a 30 ha, irrigated, laser-leveled field in Yolo County, California (38°36′N, 121°50′E). Irrigation is primarily by furrow irrigation. The site has a Mediterranean climate with annual mean temperature of 16.1 °C and average annual precipitation of 564 mm (Fig. 1). The major soil type at the site is Myers clay (fine, montmorillonitic, thermic Entic Chromoxererts). The site was managed under ST through fall 2000 and then converted to no-till in fall 2001. Following maize (*Zea mays* L.) in 2002, the field was seeded to winter wheat (*Triticum aestivum* L.). Selected chemical and physical properties of the soil at the 0–15-cm depth are reported in Lee et al. (2006).

The site was split into two fields in October 2003, with the north half of the site under full tillage operations and the south half remaining under no-till. The tillage operations consisted of one pass each of deep ripping to 45 cm, stubble disking, disking to 15 cm, grading, and listing beds. Both fields remained fallow until maize was planted on April 12 and 13, 2004. At planting, urea-ammonium nitrate (32–0–0) was band applied (10-cm depth) at a rate of 55 kg N ha^{-1}. An additional 21 kg N ha^{-1} was broadcast applied as 8–24–6. In addition, 168 kg N ha^{-1} of fertilizer N was side dressed at 15-cm depth on May 24 and 25, 2004. The maize was harvested on September 16, 2004.

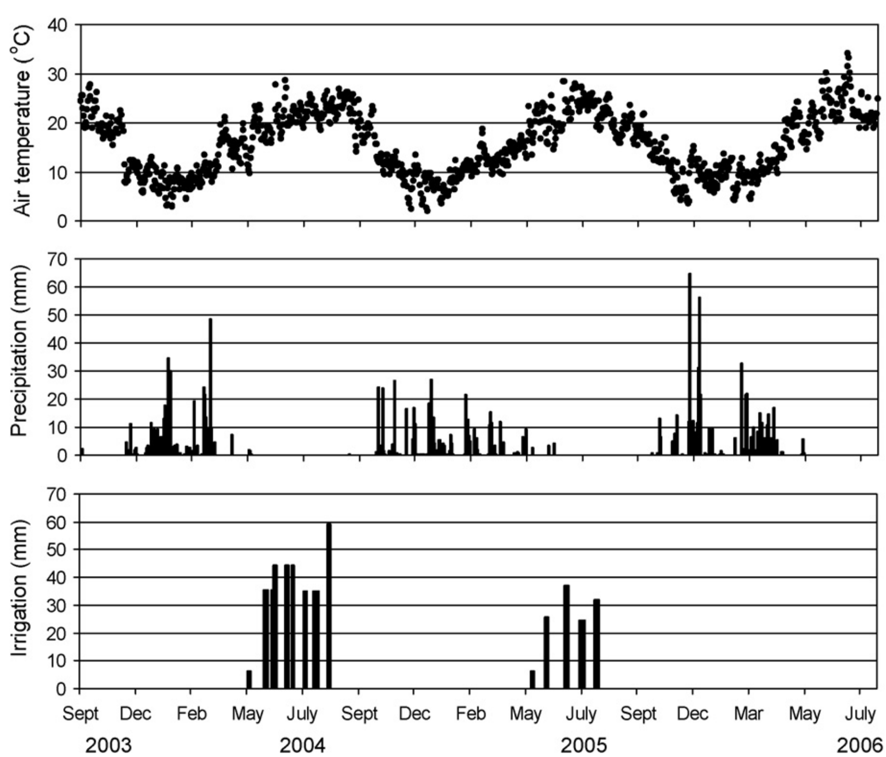

Fig. 1. Daily average air temperature, precipitation, and irrigation from 2003 to 2006 at the study site.

In May 2005, stubble was chopped in both fields, with three bed disc (to 15 cm) passes on the north side of the field and two passes on the south. Both fields also had one mulcher pass and pre-emergent herbicide incorporated. Male sunflowers (*Helianthus annuus* L.) were planted on May 16, 2005, and females were planted on May 23. Fertilizer (UAN-32) was applied at a rate of 90 kg N ha^{-1} in a side-dress application on June 17–18. The male sunflowers were disked in on August 29, and harvest occurred on October 8–10. After the sunflower harvest, both fields were again stubble chopped and had two bed-disk passes, with two mulcher passes on the north side of the field and one pass on the south. On November 19, 2005, 'Sierra' chickpea (*Cicer arietinum* L. cv. Sanford), inoculated with a granular form of *Mesorhizobium ciceri* (Agriform, Woodland, CA), was sown on beds.

Over the course of the experiment, the north side of the field represented a standard tillage (ST) field and the south side represented various degrees of minimum tillage (MT) field.

2.2. Measurements of CO_2, N_2O, and NO fluxes

At the initiation of the study in 2003, 30 sampling plots for gas samples were established in the field (Fig. 2). Two types of non-steady state portable chambers that cover the soil surface only (no plants) were used in the field. Insulated stainless steel chambers that moved from plot to plot and covered 0.012 m^2 of soil surface were used from September 2003 through April 2004. In May 2004, 0.051-m^2 PVC rings were installed in the field. The rings were pushed approximately 5 cm into the soil and left in place at positions in the middle of the seed bed, middle of the furrow, over the crop row between plants (when applicable), and over the side dressed band of fertilizer-N (Fig. 2). Portable PVC end caps were converted into chamber lids and were placed on top of the rings for sampling. In addition, two 0.62-m^2 auto-chambers were installed in the ST field with the capability of assessing the temporal pattern of CO_2 flux, and one auto-chamber was installed in the MT field. For the temporal pattern of N_2O flux, 24-h flux measurements were made in August 2005.

Fluxes of CO_2 and N_2O were measured approximately monthly during the fallow seasons and biweekly during the growing seasons. Measurements were taken at nine sampling plots per treatment of each sampling day. The CO_2 concentration inside the chambers was measured at 0, 30, 60, 120, 180, 240, and 300 s after placement of chambers over the soil surface with a Licor 6262 Infrared Gas Analyzer. Preliminary tests under field conditions showed that N_2O flux remained linear for the first 20 min following deployment. Thus, we sampled N_2O from the vented chambers in nylon syringes after 20 min. In 2003–2004, samples were kept in the sealed syringes and analyzed within 24 h on a Hewlett Packard 6890 series gas chromatograph (GC). In 2005–2006, samples pulled from the chambers were injected into pre-evacuated, 5.9-mL exetainers in the field and analyzed on the GC within a week. In addition, measurements of NO flux were made using a chemiluminescent NO_x ($NO + NO_2$) analyzer (Unisearch Model LMA-3), at least monthly from April to August 2004. Concentrations of NO gas were recorded at 30 s intervals for 4–5 min after placement of the chamber top (Venterea and Rolston, 2000).

Soil CO_2 flux was calculated using the measured CO_2 concentration in the non-steady-state diffusive flux estimator model (Livingston et al., 2005, 2006). Soil N_2O flux was calculated using the ambient air concentration and the measured concentration according to the linear regression model outlined in Hutchinson and Livingston (2002). Soil NO flux was calculated using a linear regression model (Venterea et al., 2003).

At the position level, CO_2 and N_2O fluxes were normalized for the time of day of sampling by applying a Q_{10} function to the data. Q_{10} values were computed as follows (Kirschbaum, 1995):

$$Q_{10} = \left(\frac{F_{\max}}{F_{\mathrm{ave}}}\right)^{(10/(T_{\max}-T_{\mathrm{ave}}))} \tag{1}$$

where $F_{\max}$ is the daily maximum gas flux, F_{ave} is the daily average gas flux, $T_{\max}$ is soil temperature measured at the time the max flux is measured, and T_{ave} is air temperature measured at the time the average flux occurred. Based on 24-h measurements of each flux, we used seasonal Q_{10} values ranging from 1.3 to 3.1 for CO_2 and 1.68 for N_2O, which were applied to the entire data set as follows (Parkin and Kaspar, 2003):

$$\text{Daily average gas flux} = R \times Q^{(\mathrm{DAT}-T)/10} \tag{2}$$

where R is the measured gas flux at time T, DAT is the daily average air temperature and Q is the Q_{10} value. The data set was categorized into four seasons each year based on trends in monthly mean

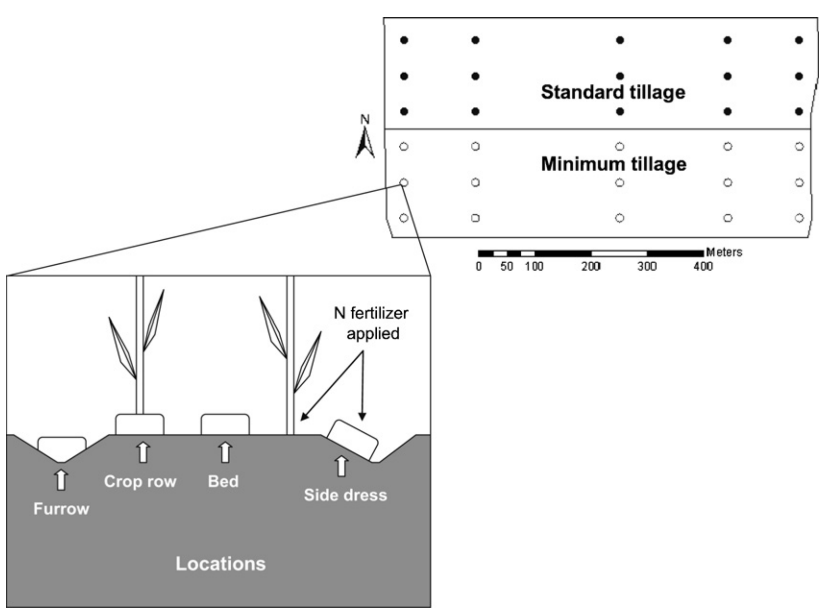

Fig. 2. Location of 30 sampling plots and closed chambers at each plot.

precipitation and air temperature (Fig. 1). The four seasons were (i) December–February, (ii) March–May, (iii) June–September, and (iv) October–November. A time-weighted average over a season was computed by multiplying the number of days in a sampling period by averaged gas fluxes for the corresponding period and dividing the sum of the products by the total number of days. The effect of position on soil gas flux was determined by using the aggregated seasonal flux data. A time-weighted average over a growing season was also computed for maize, sunflower, and chickpea.

To extrapolate the flux at the position level to the whole field level, the Q_{10}-corrected flux was normalized by accounting for the percent of surface area each chamber position occupied in the field. Of the 30-ha field, the bed, crop row, furrow, and side dress consisted of approximately 10, 10, 5, and 5 ha. The area-corrected data were used to determine the effect of tillage on soil gas flux at the field level.

2.3. Measurements of soil moisture, soil temperature, and air temperature

During each gas flux sampling, soil moisture was measured using a portable time domain reflectometery probe (HydroSense, Decagon Devices, Inc., Pullman, WA) over a depth interval from 0 to 12 cm. A calibration curve was generated by a polynomial regression of probe values to volumetric water content values (determined gravimetrically) for the top 0–12 cm of soil collected in the field. Soil temperature at the 5-cm depth was also recorded using a thermistor (Spectrum Technologies, Plainfield, IL). Air temperature was measured at the Davis CIMIS (California Irrigation Management Information System) weather station via a thermistor 1.5 m above the soil surface.

2.4. Statistical analysis

2.4.1. Mixed model ANOVA

We selected a mixed model ANOVA for a coarse analysis of tillage and position effects on CO_2 and N_2O fluxes, while accounting for confounding effects by the changes in crops each year and the varying timing shifts of tillage, fertilizer, and irrigation management (Littell et al., 2006). The gas flux data were assumed to be independent each year at each plot. At each plot, gas flux measurements were considered as repeated over time and across positions within the plot.

At both position and field levels, data from November 2003 to February 2004 were not used in the mixed model ANOVA because flux measurements were made only on the bed positions during this period. Outliers were checked by visual inspection of the

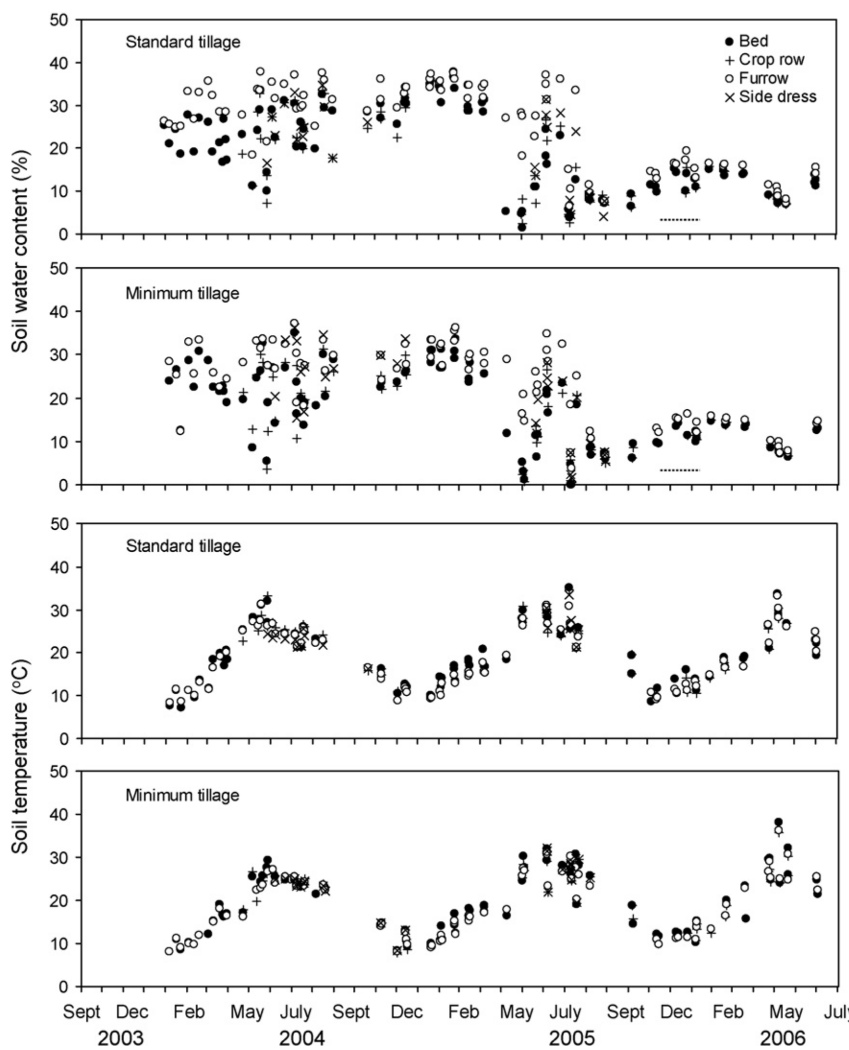

Fig. 3. Soil-water content in the 0–12 cm depth (top) and temperature in the 0–5 cm depth (bottom) from 2003 to 2006. Dashed line represents the period of substantial flooding when the field was often not physically accessible.

residual plot of the mixed model and then removed for a better model fit. A log-transformation did not work for the mixed model ANOVA, since it did not lead to normality of the residuals or improve the fit of the model.

2.4.2. Boundary line approach

A boundary line approach was used to establish the field-scale relationship between CO_2 or N_2O flux and soil-water content or soil temperature when large spatial and temporal variability in their relationships is expected (Webb, 1972; Elliott and de Jong, 1993; Schmidt et al., 2000). The boundary lines were assumed to represent optimum CO_2 or N_2O flux for each selected factor when no other factors were limiting (Webb, 1972). A boundary line was then fitted to the points that were the 99% percentiles of all gas data points in each of eight equidistant sections of soil-water content or soil temperature (Schmidt et al., 2000).

3. Results and discussion

3.1. Soil-water content and temperature

There was no major seasonal change in soil-surface water content from 2003 to 2005 because of irrigation in the summer months and winter rainfall (Fig. 3). In 2006, soil-water content started to develop a cyclic pattern when the rain-fed chickpea was planted. Winter 2005–2006 had the most substantial flooding of any years of the experiment, and the field was often not physically accessible during that time. As a result, we were not able to measure the level of soil-water content under chickpea during the peak wet periods. Among all seed bed positions, the highest soil-water content was generally observed in furrows. Tillage appears to have a minor effect on soil-water content, partly due to the confounding effects of other factors, such as soil texture.

Surface soil temperature showed clear seasonal patterns and mostly followed air temperature changes (Figs. 1 and 3). The effects of tillage and position in the seed bed on soil temperature were not apparent at the field scale level.

3.2. Carbon dioxide emissions

3.2.1. Effect of season

Seasonal CO_2 flux ranged from 4.6 to 46.9 kg C ha^{-1} day^{-1} for ST and 4.8 to 52.4 kg C ha^{-1} day^{-1} for MT over a 3-year period from 2004 to 2006. The cyclic patterns of CO_2 emission were evident during the growing season (Fig. 4). Peak soil CO_2 fluxes were usually measured during June, July, August, and September after planting and the beginning of irrigation. As expected, season had a significant effect on CO_2 emissions for the different seed bed positions (Table 1) and at the field scale (Table 2). This suggests that seasonal variations of CO_2 emissions primarily coincided with patterns of crop growth through autotrophic root respiration.

The magnitude of seasonal CO_2 flux was significantly different across years. The average CO_2 flux during the growing season was 15.2, 6.6, and 2.6 Mg C ha^{-1} in MT and 14.2, 8.5, and 2.6 Mg C ha^{-1} in ST for 2004 (maize), 2005 (sunflower), and 2006 (chickpea), respectively (Fig. 5). During the fallow/winter season of

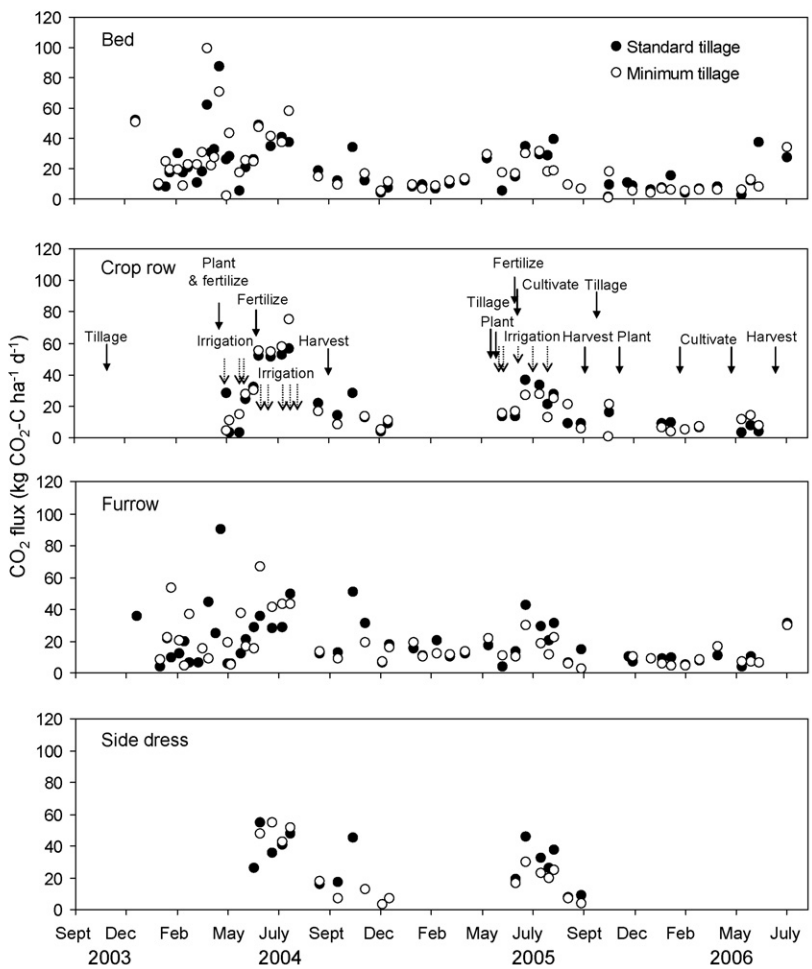

Fig. 4. Daily average carbon dioxide flux from irrigated soils under standard tillage and minimum tillage from 2003 to 2006.

Table 1
CO_2 emissions across four seed bed positions in and between rows (n = 562).

Factor	Ndf	Ddf	*F* value	Pr > *F*
Position	3	129	2.64	0.052
Year	2	74	93.5	<0.0001
Season	3	157	24.78	<0.0001
Position × tillage	3	129	2.05	0.110
Year × season	5	157	4.86	0.000
Position × season	9	165	3.02	0.002
Position × tillage × season	10	165	2.45	0.010

There is one outlier whose a residual was larger than 300 kg C ha^{-1} day^{-1} and excluded from the mixed model ANOVA. Factors are four seed bed positions (in the bed, crop row, furrow, and side dress), 3 years (2004, 2005, and 2006), and four growing seasons (December to February, March to May, June to September, and October to November). Tillage (standard and minimum tillage) was considered a confounding factor at the position scale. Pr > *F* 0.05 represents a significant difference. Abbreviations: Ndf, numerator degrees of freedom; Ddf, denominator degrees of freedom.

Table 2
Tillage and CO_2 emissions at the field scale (n = 242).

Factor	Ndf	Ddf	*F* value	Pr > *F*
Tillage	1	74	0.03	0.853
Year	2	74	61.12	<0.0001
Season	3	74	38.38	<0.0001
Year × season	5	74	5.02	0.001
Tillage × season	3	74	1.19	0.320

Flux was area-averaged over all four positions in the bed, crop row, furrow, and side dress. There was one outlier whose a residual is larger than 250 kg C ha^{-1} day^{-1}. This outlier was excluded from the mixed model ANOVA. See footnote in Table 1.

2003–2004, 2004–2005, and fall 2005, CO_2 flux was approximately 10.0, 4.1, and 3.7 Mg C ha^{-1} in MT, respectively. The corresponding CO_2 flux in ST was 8.9, 6.4, and 2.5 Mg C ha^{-1}. Similarly, the significant season and annual interaction suggests that the magnitude of the effect of season on CO_2 emissions shows that crop type is most likely determining the annual rates of soil-C cycling through autotrophic root respiration, heterotrophic microbial respiration as driven by annual soil-C inputs (West and Marland, 2002). A pattern of annual emissions seems to be further controlled by the multi-year crop rotation sequence, which corresponds to longer-term farm management practices. For example, different N-fertilizer and irrigation management practices for different crops affected soil C cycling and CO_2 emissions.

3.2.2. Effect of seed bed position

Daily average CO_2 flux across a seed bed was observed as high as 204.8 kg C ha^{-1} day^{-1} in ST and 739.1 kg C ha^{-1} day^{-1} in MT, with coefficient of variation values ranging from 16 to 219% (data not shown). Average seasonal CO_2 flux over the entire sampling period was for the ST 19.6, 15.3, 17.7, and 33.4 kg C ha^{-1} day^{-1} and for the MT 18.6, 16.6, 18.5, and 21.5 kg C ha^{-1} day^{-1} in the bed, crop row, furrow, and side dress, respectively (Fig. 4).

The gross effect of seed bed position on CO_2 emissions was not significant (Table 1). There was also no significant seed bed position and tillage interaction. However, seed bed position and season interaction had a significant effect on CO_2 emissions because CO_2 emissions from the furrow positions were high, particularly in October and November 2004, compared with the other seed bed positions and seasons. This possibly led to distinct seasonal emission patterns between the furrow and the other seed bed positions. In addition, the magnitude of differences in CO_2 flux between seed bed positions was generally greater in October–February than March–September. During the fallow/winter season, crop residues were often relocated from the other positions and accumulated in the furrow by harvest operations and/or rainfall events, while soil-water content in the furrow is not limiting at this time of the year. Presumably, these conditions led to enhanced CO_2 emissions from the furrows. As root activity has been found to strongly affect spatial and temporal variability of CO_2 emissions (Rochette et al., 1991), high CO_2 flux is usually expected in the rows relative to the interrows due to a higher root density during the growing season. However, the pattern was less apparent between the four seed bed positions, as masked by high spatial variability of CO_2 emissions at the position scale.

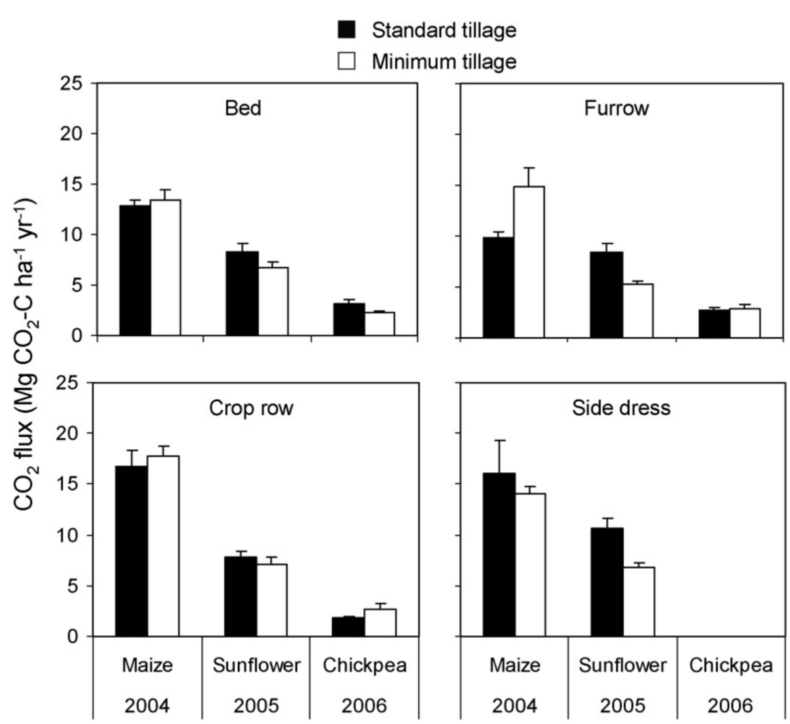

Fig. 5. Carbon dioxide fluxes as affected by tillage and position during the growing seasons from 2004 to 2006. Error bars are standard errors.

The CO_2 flux in the furrow was particularly high in ST compared to MT in October–November, resulting in the significant interaction of tillage, seed bed position, and growing season. On average, seasonal CO_2 flux was slightly higher in the bed but lower in the crop row and furrow under ST than MT. This suggests that seed bed position and tillage interaction affected seasonal CO_2 emissions at the seed bed scale. These emission patterns have been found to be closely associated with level of C inputs from crop residue in previous years during the fallow/winter season (Jensen et al., 1997; Paul et al., 1999), through input from root biomass, root turnover and rhizodeposition of the crop during the growing season (Hendry et al., 1999; Frank et al., 2006). Hendry et al. (1999) reported approximately 75% of annual CO_2 production coming from roots in summer, typically coinciding with the period of maximum plant growth. The relatively small CO_2 flux observed during the cold fallow/winter season was likely due to an absence of active root respiration across the positions.

3.2.3. Effect of tillage

The difference in CO_2 flux between MT and ST varied seasonally from -6.3 to $8.2\ kg\ C\ ha^{-1}\ day^{-1}$, with no apparent temporal patterns (Fig. 4). We found no gross effect of tillage on CO_2 emissions at the field scale (Table 2), suggesting that a short-term reduction in the rate of soil C cycling by MT was negligible. Daily CO_2 fluxes also did not differ by tillage at the position scale. A tillage by season interaction was not observed for the CO_2 emissions, indicating that seasonal emission patterns were not largely influenced by tillage.

For irrigated fields, others have also found no significant reduction in soil CO_2 emissions under no-till compared with conventional tillage with continuous maize or maize-soybean rotation during the growing season (Mosier et al., 2006). This is possibly attributed to the fact that the effect of tillage on CO_2 emissions was only short-lived (Reicosky et al., 1997; Calderón et al., 2001; Calderón and Jackson, 2002; Jackson et al., 2003). Calderón and Jackson (2002) showed that rototillage and disking increased soil-CO_2 flux significantly within 9 days after tillage due partly to degassing of dissolved CO_2, but the effect of tillage was immediately reversed by a subsequent irrigation event. In this study, the CO_2 flux was higher in MT than ST at the furrow position when maize was grown (Fig. 5). However, CO_2 flux was reduced in MT compared with ST in the furrow and side dress positions when sunflower was grown. These results indicate that at least a portion of the observed changes in CO_2 emissions is related to changes in tillage. Furthermore, they support previous studies' observations that emissions could be affected by tillage for a short period of time, yet result in smaller changes in soil respiration over the longer term (Franzluebbers et al., 1995; Jackson et al., 2003).

3.3. Nitrous oxide emissions

3.3.1. Effect of season

There was a significant effect of growing season on N_2O emissions, irrespective of spatial scale (Tables 3 and 4). Factors controlling seasonal N_2O emissions may include management practices, particularly fertilization, irrigation, selected crop, and temporal climatic variations. Although soil-water conditions were expected to be conducive to N_2O production during the early spring, there was probably not sufficient mineral N in the soil. There was a general increase in N_2O fluxes following the application of fertilizer N and irrigation, followed by much smaller N_2O fluxes in subsequent weeks (Fig. 6). As expected, the largest N_2O emissions occur within several days after N-fertilization during the 2004 (maize) and 2005 (sunflower) growing seasons. The daily N_2O fluxes ranged up to $161.2\ g\ N\ ha^{-1}\ day^{-1}$ in 2004 and $66.8\ g\ N\ ha^{-1}\ day^{-1}$ in 2005 (data not shown). This pattern was generally consistent over growing seasons at both the seed bed and field scale level. Seasonal N_2O fluxes ranged from 0 to $24.2\ g\ N\ ha^{-1}\ day^{-1}$ for ST and from 0 to $98.9\ g\ N\ ha^{-1}\ day^{-1}$ for MT across all the positions.

Table 3
N_2O emissions at four positions in and between rows ($n = 461$).

Factor	Ndf	Ddf	F value	Pr > F
Position	3	132	1.39	0.249
Year	2	73	2.65	0.078
Season	3	100	11.16	<.0001
Position × tillage	3	132	2.92	0.036
Year × season	4	100	1.83	0.129
Position × season	9	121	3.69	0.000
Position × tillage × season	9	121	2.81	0.005

There were five outliers whose residual was larger than $110\ g\ N\ ha^{-1}\ day^{-1}$. The outliers were excluded from the mixed model ANOVA. See footnote in Table 1.

For MT, average N_2O flux decreased from $8.53\ kg\ N\ ha^{-1}\ year^{-1}$ across the positions for the 2004 growing season (maize) to $3.84\ kg\ N\ ha^{-1}\ year^{-1}$ for the 2005 (sunflower) and $2.03\ kg\ N\ ha^{-1}\ year^{-1}$ for the 2006 growing seasons (chickpea) (Fig. 7). In ST, N_2O fluxes were 3.83, 2.91, and $1.28\ kg\ N\ ha^{-1}\ year^{-1}$ in 2004, 2005, and 2006, respectively. These decreases in emissions were due to the decreased level of fertilizer N input for sunflower and chickpea compared to maize. A large proportion of the annual N_2O flux was also emitted during the fallow period and/or the winter period, ranging from 0 to $22.8\ kg\ N\ ha^{-1}\ year^{-1}$ across the positions in the bed, crop row, and furrow. In our study, N_2O emissions during the fallow/winter season accounted for 4–45% and 3–18% of the total annual emissions in ST and MT, respectively. Maljanen et al. (2003) reported that N_2O emissions during the winter period accounted for 15–60% of the total annual emissions from a boreal organic soil. Whereas in a semiarid climate, N_2O emissions during the fallow season could be lower (Mosier et al., 2006), under our irrigated Mediterranean climatic conditions, the emission patterns of N_2O across a year did not differ significantly between seasons.

3.3.2. Effect of seed bed position

For the ST, average N_2O fluxes over the entire period of sampling were 5.4, 5.5, 5.8, and $19.7\ g\ N\ ha^{-1}\ day^{-1}$ in the bed, crop row, furrow, and side dress, respectively, whereas they were 8.0, 13.5, 8.6, and $42.8\ g\ N\ ha^{-1}\ day^{-1}$ for MT. Large emissions occurred directly in the side dress positions where the fertilizer-N was applied (Figs. 6 and 7). There was also the large flux in the crop row of the maize under MT. With a few exceptions, the smallest emissions tended to be from the furrow locations. Across the positions, the seasonal N_2O flux could be potentially as high as $26.9–293.3\ g\ N\ ha^{-1}\ day^{-1}$. Large spatial variability across seed bed positions presents a challenge in calculating field-scale fluxes due to large uncertainty associated with determining the area of emission for each seed bed position.

Table 4
Tillage and seasonal N_2O emissions[†] at the field scale ($n = 181$).

Factor	Ndf	Ddf	F value	Pr > F
Tillage	1	73	0.44	0.510
Year	2	73	0.82	0.443
Season	3	73	12.98	<0.0001
Year × season	4	73	2.13	0.086
Tillage × season	3	73	4.14	0.009

Flux was area-averaged over all four positions in the bed, crop row, furrow, and side dress. There were four outliers whose a residual were larger than $70\ g\ N\ ha^{-1}\ day^{-1}$. The outliers were excluded from the mixed model ANOVA. See footnote in Table 1.

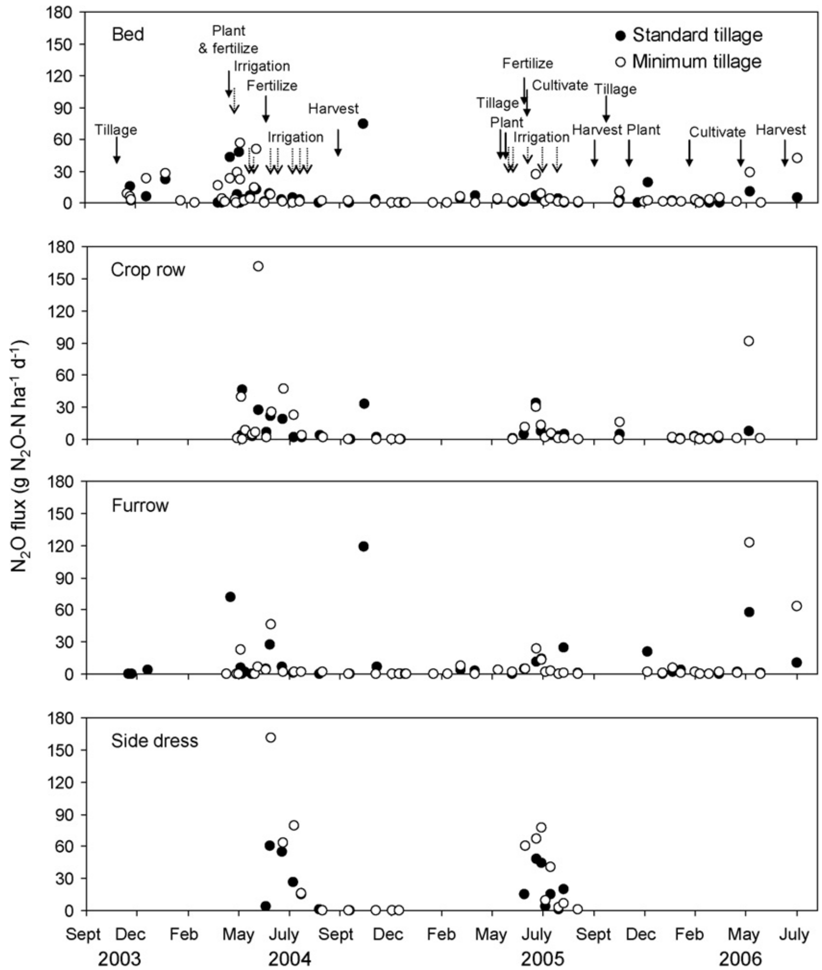

Fig. 6. Daily average nitrous oxide flux from irrigated soils under standard tillage and minimum tillage from 2003 to 2006.

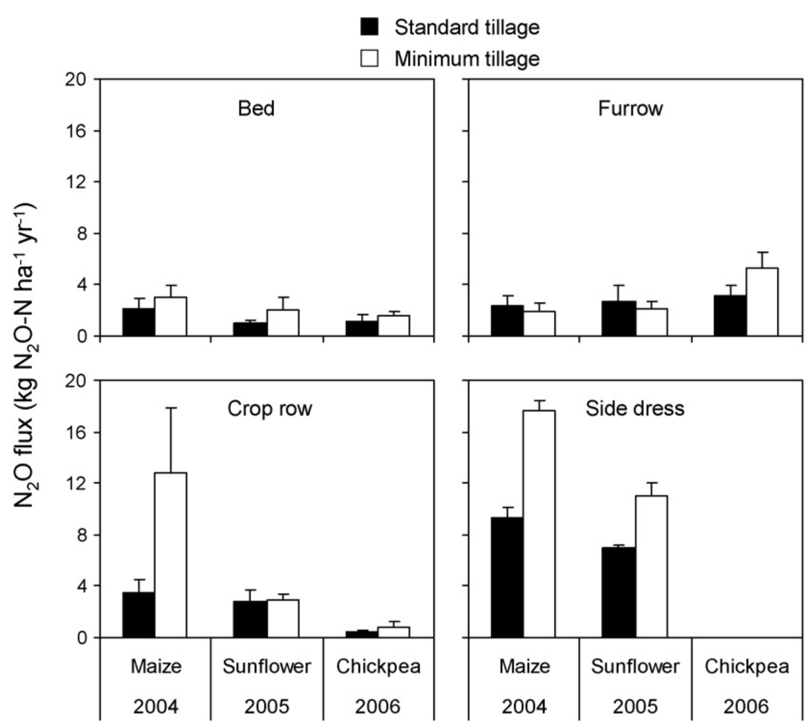

Fig. 7. Nitrous oxide fluxes as affected by tillage and position during the growing seasons from 2004 to 2006. Error bars are standard errors.

The emission patterns were not always consistent across seed bed positions and at the field scale. The gross effect of seed bed position on N_2O emissions was not significant (Table 3), reflecting the stochastic nature of N_2O emissions in space (Folorunso and Rolston, 1984). However, N_2O flux in the side dress position was significantly ($P < 0.05$) greater than the fluxes from the other seed bed positions at the times of side-dress fertilizer-N applications (Fig. 6). As a result, the interaction between seed bed position and growing season had a significant effect on N_2O emissions. Overall, the interaction of seed bed position and growing season may contribute to the irregular patterns of N_2O emissions at the field scale as fertilizer-N rate and timing are usually adjusted annually according to the crop grown.

3.3.3. Effect of tillage

At the position scale, tillage appeared to have a small effect on N_2O emissions because tillage effect on N_2O flux was only significant at the side dress for the seed bed position ($P = 0.03$) (Fig. 8). Although N_2O flux was generally higher in MT than ST with time at the field scale, several unexpectedly high flux values seem to mask a gross tillage effect on N_2O fluxes (Table 4). The maximum difference in seasonal N_2O flux between ST and MT was 20.3 g N ha^{-1} day^{-1} which was observed in March–May 2004. During this period, the maximum daily difference between the fields was 68.6 g N ha^{-1} day^{-1} immediately following the application of fertilizer N and irrigation (data not shown).

The effect of tillage and season interaction on N_2O emissions was significant mainly due to an abrupt increase in N_2O emissions at one location in the ST field ($\approx$66.7 g N ha^{-1} day^{-1}) in October 2004. This high value for N_2O emission suggests the presence of 'hotspots' in which processes regulating soil denitrification are spatially correlated over a short-range and vary over time. Pennock et al. (1992) and Cambardella et al. (1994) showed that many soil properties associated with landscape-scale denitrification were moderately correlated over a short distance, ranging up to 75 m. However, hotspots of denitrification activity were usually observed when soil conditions for denitrification activity were limited (van Kessel et al., 1993), potentially misleading the effect of tillage on N_2O emissions. Overall, this suggests that there were no clear patterns of temporal variation in N_2O emissions by tillage due to their stochastic nature at the field scale (Mosier et al., 2006). These results are in contrast to the results by Six et al. (2004) who found a general increase in N_2O fluxes in recently established no-tillage systems compared to conventional tillage systems, especially in humid climates. This contrast is probably due to the greater disturbance and consequently less compaction in this minimum tillage system than in the no-tillage systems of the Great Plains and Corn Belt.

3.4. Nitric oxide emissions

For the MT, nitric oxide flux from soils during the 2004 maize growing season were on average 0.6, 4.6, 2.7, and 10.6 g N ha^{-1} day^{-1} in the bed, crop row, furrow, and side dress positions, respectively; they were 1.9, 10.9, 10.9, and 15.7 g N ha^{-1} day^{-1} in the ST system (Fig. 9). Emissions of NO occurred mostly at sampling locations directly over the side dress and crop row, and to a lesser extent in the furrow during the growing season. In general, NO emissions in the seed bed seem to be related to band-applied N-fertilizer, while NO emissions from the furrow likely responded to irrigation. It has been shown that the emission of both N_2O and NO from agricultural soils were linearly related to the rate of N application (Veldkamp and Keller, 1997; Venterea and Rolston, 2000; Liu et al., 2005). It is also known that the main source of NO is the nitrification process (Anderson and Levine, 1986) and NO emissions by nitrification tend to increase with increasing soil-water content under aerobic conditions (Bollmann and Conrad, 1998). Our study further showed that localized N fertilizer increases NO emissions.

At the scale of the seed bed, NO emissions were approximately two to four times higher in ST than MT. Liu et al. (2005) also showed higher NO emissions from an irrigated field under

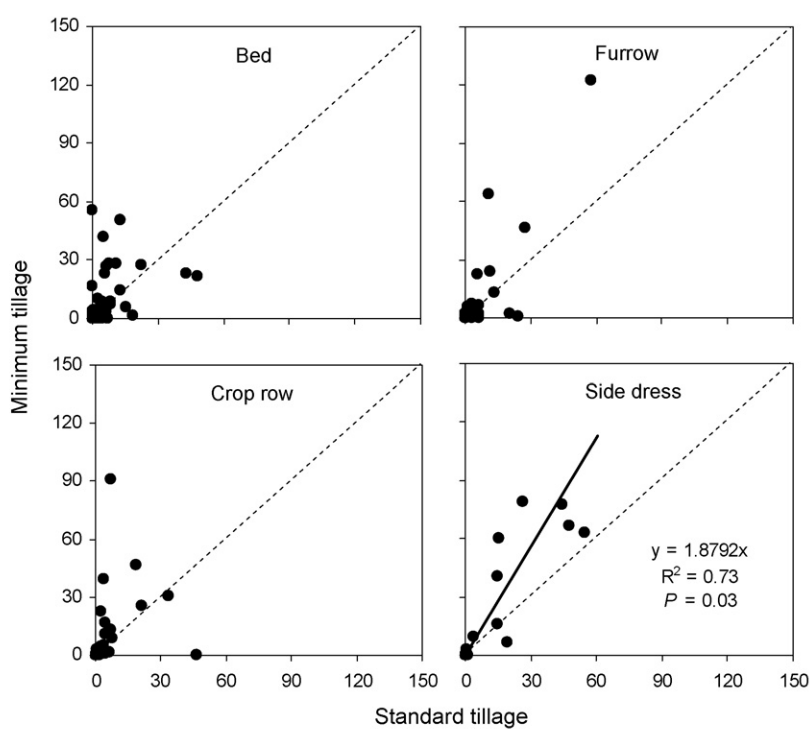

Fig. 8. Effect of tillage on daily nitrous oxide flux (g N_2O-N ha^{-1} day^{-1}) from irrigated soils.

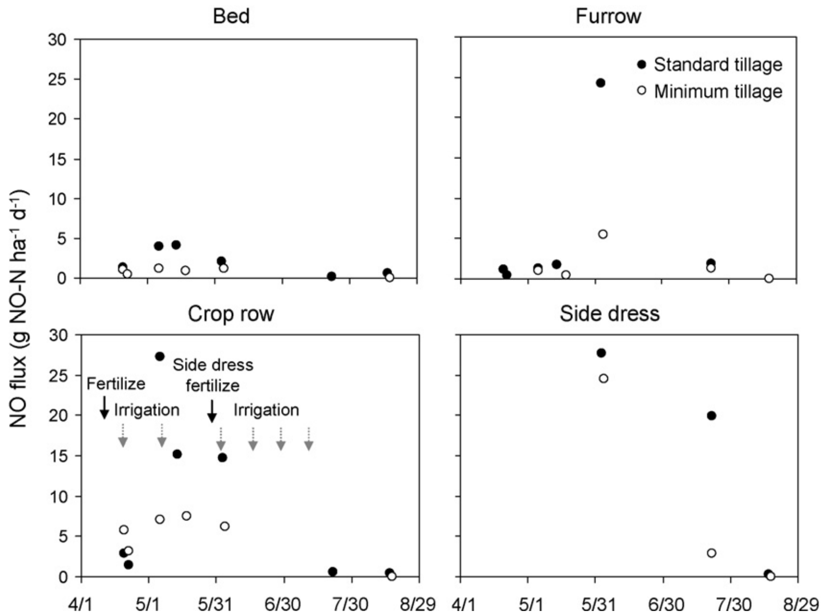

Fig. 9. Nitric oxide flux from irrigated soils under standard tillage and minimum tillage during the 2004 growing season.

conventional tillage than no-till. On average, N_2O/NO emission ratios over the sampling period varied widely from 8.9 to 32.7 for MT and 2.2 to 9.5 for ST at the position scale. The N_2O/NO ratios were generally higher in the middle of the seed bed compared with the other seed bed positions. The N_2O/NO ratios were comparable to results observed earlier in maize fields (Liu et al., 2005), which remain highly variable even within a single field or season (Skiba et al., 1997). Typically, more NO is produced than N_2O under soil conditions that show nitrifying activity (Venterea and Rolston, 2000). Therefore, N_2O/NO ratios could indicate changes in soil conditions or the dominant process of N transformation. Based on the N_2O/NO ratios, ST tends to enhance nitrifying activity rather than denitrifying activity, which confirms findings observed earlier at our site (Lee et al., 2006).

3.5. Overall effect of soil water and temperature

3.5.1. Carbon dioxide

The boundary line analysis suggest that there was a large difference in the relationship between soil-water content and soil respiration activity among crops at the field scale (Fig. 10). Optimum CO_2 fluxes under maize in 2004 strongly increased with increasing soil-water content, but the relationship was not observed for sunflower and chickpea. Clearly, optimum CO_2 fluxes in response to soil-water content are different for these 3 crops. It is also possible that the optimum CO_2 fluxes for these 3 crops are partially driven by different irrigation management practices for these crops. Studies have also shown that CO_2 emissions would be more closely related to subsurface soil water than surface water. For example, Fierer et al. (2005) showed that rainfall patterns strongly affected CO_2 production rates throughout the soil profile of a California annual grassland whereas Hendry et al. (1999) observed the greatest CO_2 production in the saturated zone during the non-growing season.

The relationship between optimum CO_2 flux and temperature was generally consistent across years (Fig. 10). The maximum CO_2 fluxes were usually observed at temperature ranges from 25 to 30 °C. Under field conditions, CO_2 flux began to increase in March and April because of the warming of the soil and resulting increased microbial respiration (Fig. 4). After planting and the onset of irrigation, CO_2 fluxes increased following an increase in soil temperature during June, July, August, and September. During these months, clear cyclic patterns in CO_2 flux were apparent with the peak fluxes occurring at a soil surface temperature range between 25 and 30 °C. These annual patterns of increasing and decreasing CO_2 flux generally followed changes in soil temperature and remained consistent throughout the years. However, the relationship between soil respiration and temperature remained highly variable when the temperature was low (<15 °C) or high (>30 °C). Soil temperature above 30–35 °C tends to limit CO_2 emissions, because soil water becomes often limiting at those high temperatures recorded between irrigation events (Wardle and Parkinson, 1990). This was particularly the case when maize was grown because maize required more irrigation than the other crops.

In general, the large seasonal variations of water content and/or temperature have a major effect on CO_2 emissions under field conditions (Franzluebbers et al., 1995). Both the magnitude and pattern of changes in optimum CO_2 fluxes were not always consistent with changes in the selected soil variables over years due to the confounding effect of growing different crops. Crop type is likely the overall main driver of soil CO_2 flux at the field scale. Franzluebbers et al. (1995) also showed that soil CO_2 emissions would respond differently to seasonal variations in soil-water content and temperature depending on crop type.

3.5.2. Nitrous oxide

The majority of the measured N_2O flux values were highly variable and generally low over the range of soil-water content (Fig. 11). This clearly confirms that N_2O emissions were limited by other controlling factors, such as soil mineral N (Sehy et al., 2003). Nevertheless, a scattergram of N_2O flux and soil-water content shows that N_2O emissions potentially increased with increasing soil-water content. In our study, a sharp increase in N_2O emissions was observed at soil-water content ranges between 7 and 12%. The optimum N_2O emissions occurred at 12–30% water content, which is in agreement with Drury et al. (2003). However, we observed that N_2O emissions could be limited in extremely wet conditions (e.g., at soil-water content >35%). While anaerobic zones increased at high water content, increased denitrification activity would

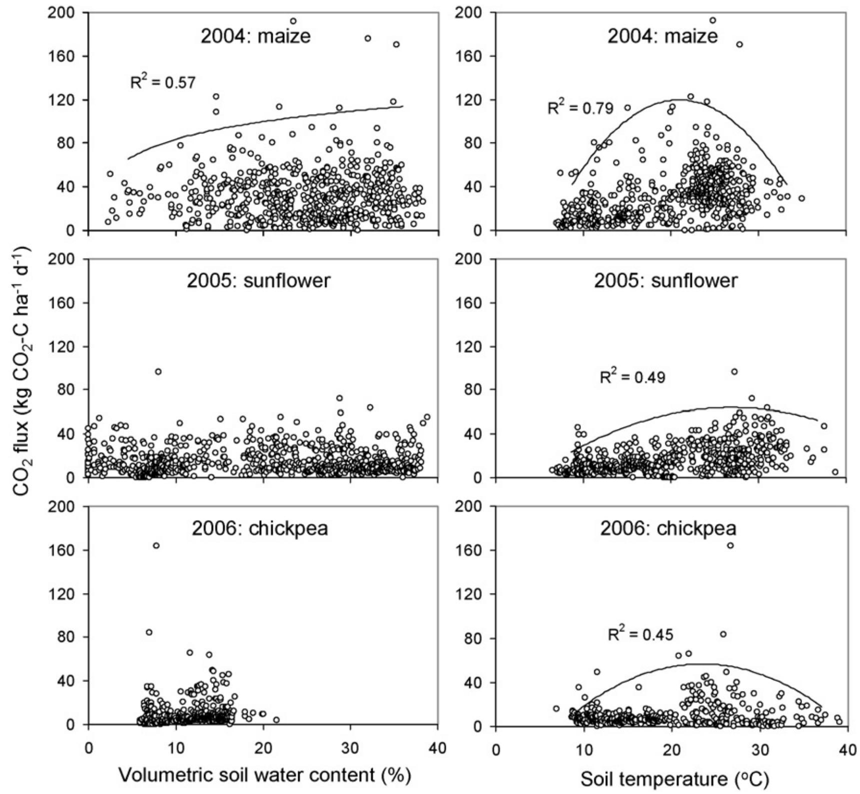

Fig. 10. Scattergrams and boundary lines for soil-water content (0–12 cm) and temperature (0–5 cm) plotted against daily average carbon dioxide flux.

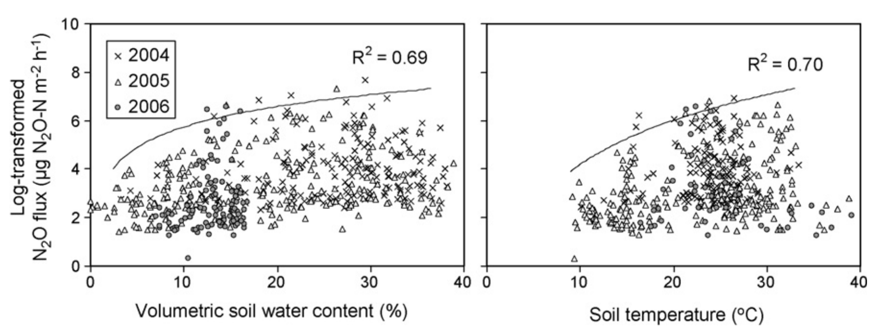

Fig. 11. Scattergrams and boundary lines for soil-water content (0–12 cm) and temperature (0–5 cm) plotted against daily average nitrous oxide flux.

result in a significant local N deficiency (Drury et al., 2003). In addition, poor aeration may prevent N gas diffusivities at the soil surface (Elliott and de Jong, 1993). Such a decrease in N_2O emissions could also be attributed to rapid reduction from N_2O to N_2 under high water content (Del Grosso et al., 2000). Therefore, the changes in soil water would explain part of the observed emission patterns. Although no gross tillage effect on N_2O emissions was observed, optimum N_2O flux was predicted to be 1.3–4.7 times higher in MT than ST and occur in the range of 25–40% soil-water content based on the boundary lines (data not shown). Tillage may also affect N_2O flux in response to changes in soil water (Lee et al., 2006).

Optimum N_2O emissions increased with increasing soil temperature (Fig. 11). Little or no N_2O fluxes were observed at soil temperatures below 10 °C. Microbial nitrification and denitrification could be limited at low soil temperature ranges (Powlson et al., 1988; Smith et al., 1998; Sehy et al., 2003). Particularly at low temperatures, N_2O flux ranges tend to be highly confounded by other factors, such as soil mineral N and water content (Conen et al., 2000; Sehy et al., 2003). N_2O fluxes did not exceed 16 μg N m^{-2} h^{-1} (linear scale) at high temperature (>35 °C) (Fig. 11). Similar to the effect of temperature on CO_2 emissions, low water content could be preferentially limiting denitrification activity at high temperature (Smith et al., 1998). Therefore, the spatial and temporal variability of N_2O emissions could be in part explained by the interactive effect of soil-water content and temperature.

4. Conclusions

To develop economically efficient as well as effective policies in mitigating and reducing GHG emissions in irrigated farming systems, the underlying processes leading to variable GHG emissions across the field and its quantification have to be better understood. In irrigated soils, the interactions between tillage, season, and position across the field had a significant effect on both

CO_2 and N_2O emissions. Seasonal and annual CO_2 emissions were likely a function of crop growth and type, respectively, whereas N_2O emissions tend to correspond to the timing and amount of N fertilization and irrigation events. No gross effect of tillage or position on CO_2 and N_2O emissions were found. Therefore, the short-term use of MT for irrigated soils did not appear to decrease soil respiration rates across the field but may have some adverse effects due to increased N_2O emissions in some places within the field, i.e. tillage interacted with seed bed position for both CO_2 and N_2O emissions. In the seed bed position where fertilizer-N was side dressed, for example, N_2O flux was 1.9 times higher under MT compared to ST. At the same time, the flux was significantly greater than the fluxes from the other seed bed positions. The NO emissions occurred mostly at the seed bed position where N-fertilizer was side dressed and band-applied, and to a lesser extent in the furrow after irrigation events.

The boundary lines suggest that soil-water content and temperature were generally related to both optimum CO_2 and N_2O emissions. However, at the field level, relationships remained highly variable and complex due to tillage, position in the field, and season interactions. Moreover, the optimum CO_2 fluxes in response to soil-water content and temperature would be depended on the different crops as a crop appeared to be the main driver of maximum CO_2 flux. As rates of N-fertilizer and irrigation recommended are dependent on farmers' crop choice, N_2O emissions may be also related to crop type. N_2O emissions were expected to increase by MT when soil-water content was conducive to active denitrification. In general, high temporal and seasonal variability of the emissions is largely confounded by crop and specific soil conditions. Therefore, particularly for irrigated soils, position-specific variations in GHG emissions between ST and MT should be accounted for to improve estimates of CO_2 and N_2O losses at the field scale.

Acknowledgements

This work was funded by the Kearney Foundation of Soil Science, Project #2005.204. We thank George Lu, Emily Sharp and Jason Bartlett for gas sampling and laboratory assistance.

References

Anderson, I.C., Levine, J.S., 1986. Relative rates of nitric oxide and nitrous oxide production by nitrifiers, denitrifiers, and nitrate respirers. Appl. Env. Microbiol. 51, 938–945.

Bollmann, A., Conrad, R., 1998. Influence of O_2 availability on NO and N_2O release by nitrification and denitrification in soils. Global Change Biol. 4, 387–396.

Calderón, F.J., Jackson, L.E., 2002. Rototillage, disking, and subsequent irrigation: effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. J. Environ. Qual. 31, 752–758.

Calderón, F.J., Jackson, L.E., Scow, K.M., Rolston, D.E., 2001. Short-term dynamics of nitrogen, microbial activity, and phospholipid fatty acids after tillage. Soil Sci. Soc. Am. J. 65, 118–126.

California Energy Commission, 2005. Research roadmap for greenhouse gas inventory methods: consultant report. California Energy Commission, Sacramento, pp. 4–15.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.L., Turco, R.F., Konopka, A.E., 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58, 1501–1511.

Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., Zhao, Q., 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutr. Cycl. Agroecosyst. 49, 221–228.

Conen, F., Dobbie, K.E., Smith, K.A., 2000. Predicting N_2O emissions from agricultural land through related soil parameters. Global Change Biol. 6, 417–426.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Ojima, D.S., Kulmala, A.E., Phongpan, S., 2000. General model for N_2O and N_2 gas emissions from soils due to denitrification. Global Biogeochem. Cycl. 14, 1045–1060.

Drury, C.F., Zhang, T.Q., Kay, B.D., 2003. The non-limiting and least limiting water ranges for soil nitrogen mineralization. Soil Sci. Soc. Am. J. 67, 1388–1404.

Elliott, J.A., de Jong, E., 1993. Prediction of field denitrification rates: a boundary-line approach. Soil Sci. Soc. Am. J. 57, 82–87.

Eve, M.D., Sperow, M., Howerton, K., Paustian, K., Follet, R.F., 2002. Predicted impact of management changes on soil carbon stocks for each agricultural region of the conterminous United States. J. Soil Water Conserv. 57, 196–204.

Fierer, N., Chadwick, O.A., Trumbore, S.E., 2005. Production of CO_2 in soil profiles of a California annual grassland. Ecosystems 8, 412–429.

Folorunso, O.A., Rolston, D.E., 1984. Spatial variability of field-measured denitrification gas fluxes. Soil Sci. Soc. Am. J. 48, 1214–1219.

Frank, A.B., Liebig, M.A., Tanaka, D.L., 2006. Management effects on soil CO_2 efflux in northern semiarid grassland and cropland. Soil Till. Res. 89, 78–85.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. Soil Till. Res. 34, 41–60.

Hendry, M.J., Mendoza, C.A., Kirkland, R.A., Lawrence, J.R., 1999. Quantification of transient CO_2 production in a sandy unsaturated zone. Water Resour. Res. 35, 2189–2198.

Hook, P.B., Burke, I.C., 2000. Biogeochemistry in a shortgrass landscape: control by topography, soil texture, and microclimate. Ecology 81, 2686–2703.

Hutchinson, G.L., Livingston, G.P., 2002. Soil-atmosphere gas exchange. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. SSSA, Madison, WI, pp. 1159–1182.

Intergovernmental Panel on Climate Change, 2007. IPCC Fourth Assessment Report: Climate Change 2007 (http://www.ipcc.ch/ipccreports/assessments-reports.htm).

Jackson, L.E., Calderon, F.J., Steenwerth, K.L., Scow, K.M., Rolston, D.E., 2003. Responses of soil microbial processes and community structure to tillage events and implications for soil quality. Geoderma 114, 305–317.

Jensen, L.S., Mueller, T., Magid, J., Nielsen, N.E., 1997. Temporal variation of C and N mineralization, microbial biomass and extractable organic pools in soil after oilseed rape straw incorporation in the field. Soil Biol. Biochem. 29, 1043–1055.

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol. Biochem. 24, 753–760.

Lee, J., Six, J., King, A.P., van Kessel, C., Rolston, D.E., 2006. Tillage and field scale controls on greenhouse gas emissions. J. Environ. Qual. 35, 714–725.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., Schabenberber, O., 2006. SAS for Mixed Models, Second edition. SAS Institute Inc., Cary, NC.

Liu, X.J., Mosier, A.R., Halvorson, A.D., Zhang, F.S., 2005. Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. Plant Soil 276, 235–249.

Livingston, G.P., Hutchinson, G.L., Spartalian, K., 2005. Diffusion theory improves chamber-based measures of trace gas emissions. Geophys. Res. Lett. 32, L24817.

Livingston, G.P., Hutchinson, G.L., Spartalian, K., 2006. Trace gas emission in chambers: a non-steady-state diffusion model. Soil Sci. Soc. Am. J. 70, 1459–1469.

Maljanen, M., Liikanen, A., Silvola, J., Martikainen, P.J., 2003. Nitrous oxide emissions from boreal organic soil under different land-use. Soil Biol. Biochem. 35, 689–700.

Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J., 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J. Environ. Qual. 35, 1584–1598.

Parkin, T.B., Kaspar, T.C., 2003. Temperature controls on diurnal carbon dioxide flux: implications for estimating soil carbon loss. Soil Sci. Soc. Am. J. 67, 1763–1772.

Paul, E.A., Harris, D., Collins, H.P., Schulthess, U., Robertson, G.P., 1999. Evolution of CO_2 and soil carbon dynamics in biologically managed, row-crop agroecosystems. Appl. Soil Ecol. 11, 53–65.

Pennock, D.J., van Kessel, C., Farrell, R.E., Sutherland, R.A., 1992. Landscape-scale variations in denitrification. Soil Sci. Soc. Am. J. 56, 770–776.

Powlson, D.S., Saffigna, P.G., Kragt-Cottaar, M., 1988. Denitrification at sub-optimal temperatures in soils from different climatic zones. Soil Biol. Biochem. 20, 719–723.

Reicosky, D.C., Dugas, W.A., Torbert, H.A., 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. Soil Till. Res. 41, 105–118.

Rochette, P., Desjardins, R.L., Pattey, E., 1991. Spatial and temporal variability of soil respiration in agricultural fields. Can. J. Soil Sci. 71, 189–196.

Ryden, J.C., 1981. N_2O exchange between a grassland soil and the atmosphere. Nature 292, 235–237.

Schlesinger, W.H., 1999. Carbon sequestration in soils. Science 248, 2095.

Schmidt, U., Thoni, H., Kaupenjohann, M., 2000. Using a boundary line approach to analyze N_2O flux data from agricultural soils. Nutr. Cycl. Agroecosyst. 57, 119–129.

Sehy, U., Ruser, R., Munch, J.C., 2003. Nitrous oxide fluxes from maize fields: relationship to yield, site-specific fertilization, and soil conditions. Agr. Ecosyst. Environ. 99, 97–111.

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biol. 10, 155–160.

Skiba, U., Fowler, D., Smith, K.A., 1997. Nitric oxide emissions from agricultural soils in temperate and tropical climates: sources, controls and mitigation options. Nutr. Cycl. Agroecosyst. 48, 139–153.

Smith, K.A., 1999. After the Kyoto Protocol: can soil scientists make a useful contribution? Soil Use Manage. 15, 71–75.

Smith, K.A., Thomson, P.E., Clayton, H., McTaggart, I.P., Conen, F., 1998. Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. Atmos. Environ. 32, 3301–3309.

Smith, K.A., Conen, F., Ball, B.C., Leip, A., Russo, S., 2002. Emissions of non-CO_2 greenhouse gases from agricultural land and the implications for carbon trading.

In: van Ham, J., Baede, A.P.M., Guicherit, R., Williams-Jacobse, J.G.F.M. (Eds.), Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects. Millpress, Rotterdam, The Netherlands, pp. 669–672.

USEPA, 2006. Executive summary. In: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2004. Washington, DC, pp. 1–17.

van Kessel, C., Pennock, D.J., Farrell, R.E., 1993. Seasonal variations in denitrification and nitrous oxide evolution at the landscape scale. Soil Sci. Soc. Am. J. 57, 988–995.

Veldkamp, E., Keller, M., 1997. Fertilizer-induced nitric oxide emissions from agricultural soils. Nutr. Cycl. Agroecosyst. 48, 69–77.

Venterea, R.T., Rolston, D.E., 2000. Nitric and nitrous oxide emissions following fertilizer application to agricultural soil: biotic and abiotic mechanisms and kinetics. J. Geophys. Res.-Atmos. 105, 15117–15129.

Venterea, R.T., Groffman, P.M., Verchot, L.V., Magill, A.H., Aber, J.D., Steudler, P.A., 2003. Nitrogen oxide gas emissions from temperate forest soils receiving long-term nitrogen inputs. Global Change Biol. 9, 346–357.

Walley, F., Yates, T., van Groenigen, J.-W., van Kessel, C., 2002. Relationships between soil nitrogen availability indices, yield, and nitrogen accumulation of wheat. Soil Sci. Soc. Am. J. 66, 1549–1561.

Wardle, D.A., Parkinson, D., 1990. Interactions between microclimatic variables and the soil microbial biomass. Biol. Fert. Soils 9, 273–280.

Webb, R.A., 1972. Use of the boundary line in the analysis of biological data. J. Hort. Sci. 47, 309–319.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agr. Ecosyst. Environ. 91, 217–232.