Effects of Manure and Cultivation on Carbon Dioxide and Nitrous Oxide Emissions from a Corn Field under Mediterranean Conditions

Hadar Heller,* Asher Bar-Tal, and Guy Tamir Agricultural Research Organization
Paul Bloom and Rodney T. Venterea University of Minnesota
Dong Chen California Department of Water Resources
Yi Zhang Manitoba Agriculture, Food and Rural Initiatives
C. Edward Clapp University of Minnesota
Pinchas Fine Agricultural Research Organization

The use of organic residues as soil additives is increasing, but, depending on their composition and application methods, these organic amendments can stimulate the emissions of CO_2 and N_2O. The objective of this study was to quantify the effects of management practices in irrigated sweet corn (*Zea mays* L.) on CO_2 and N_2O emissions and to relate emissions to environmental factors. In a 3-yr study, corn residues (CR) and pasteurized chicken manure (PCM) were used as soil amendments compared with no residue (NR) under three management practices: shallow tillage (ST) and no tillage (NT) under consecutive corn crops and ST without crop. Tillage significantly increased ($P < 0.05$) CO_2 and N_2O fluxes in residue-amended plots and in NR plots. Carbon dioxide and N_2O fluxes were correlated with soil NH_4 concentrations and with days since tillage and days since seeding. Fluxes of CO_2 were correlated with soil water content, whereas N_2O fluxes had higher correlation with air temperature. Annual CO_2 emissions were higher with PCM than with CR and NR (9.7, 2.9, and 2.3 Mg C ha^{-1}, respectively). Fluxes of N_2O were 34.4, 0.94, and 0.77 kg N ha^{-1} yr^{-1} with PCM, CR, and NR, respectively. Annual amounts of CO_2–C and N_2O–N emissions from the PCM treatments were 64 and 3% of the applied C and N, respectively. Regardless of cultivation practices, elevated N_2O emissions were recorded in the PCM treatment. These emissions could negate some of the beneficial effects of PCM on soil properties.

The global atmospheric concentrations of CO_2 and N_2O are on the rise, with an average increase of 1.9 μL CO_2 L^{-1} per year from 1995 to 2005 and an increase of N_2O from a pre-industrial concentration of about 0.27 to 0.32 μL L^{-1} in 2005 (IPCC, 2007). Some of the increase in concentrations of these greenhouse gases (GHGs) can be attributed to agricultural activities, including the use of organic waste (OW) as soil amendments. The use of OW on agricultural soils has increased as a result of the necessity to recycle materials for protection of the environment, to supply nutrients to crops, and to increase or at least maintain organic matter concentrations in soil. In some cases, the local needs for disposal of excess OW result in high applications.

The regulations for the maximum load of OW to agricultural soils are based on the potential pollution of soil and water, with little or no consideration of air emissions. Organic wastes, including animal manure and municipal wastes and their composts, and crop residues (CR) enhance emissions of CO_2 and N_2O to the air compared with inorganic fertilizers (Hadas et al., 2004; Jones et al., 2005; Ding et al., 2007; Johnson et al., 2007). Rates of decomposition of OW in soil determine the amount of C that is mineralized and released as CO_2 versus the amount of C that becomes incorporated into soil organic matter (SOM) (Rochette et al., 1999). Decomposition rates of OW also greatly influence the amount of N that becomes available for plant uptake or susceptible for leaching versus that retained in SOM or lost as N_2O. The rates of decomposition and release of N from OW in soils greatly depends on the composition of the OW as long as N availability is not a limiting factor (Trinsoutrot et al., 2000).

Nitrification and denitrification processes are the main source of biogenic emissions of N_2O from soils (Tortoso and Hutchinson, 1990; Johnson et al., 2007). Nitrous oxide is an intermediate in

Published in J. Environ. Qual. 39:437–448 (2010).
doi:10.2134/jeq2009.0027
Published online 1 Feb. 2010.
Received 20 Jan. 2009.
*Corresponding author (hadarh@agri.gov.il).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

H. Heller, A. Bar-Tal, G. Tamir, and P. Fine, Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, The Volcani Center, P.O. Box 6, Bet Dagan 50250, Israel; P. Bloom, Dep. of Soil, Water and Climate, Univ. of Minnesota, St. Paul, MN 55108; R.T. Venterea and C.E. Clapp, USDA–ARS and Dep. of Soil, Water and Climate, Univ. of Minnesota, St. Paul, MN 55108; D. Chen, California Dep. of Water Resources, P.O. Box 942836, Sacramento, CA 94236; Y. Zhang, Agri-Environment Branch, Manitoba Agriculture, Food and Rural Initiatives, 36 Armitage St., Manitoba, CanadaR0J 1E0.

Abbreviations: CR, corn residues; CT, conservation tillage; GC, gas chromatography; GHG, greenhouse gas; NR, no residue; NT, no tillage; OW, organic waste; PCM, pasteurized chicken manure; SOM, soil organic matter; ST, shallow tillage.

denitrification (reduction of NO_3 to N_2) and is also an intermediate product of nitrification (oxidation of NH_4 to NO_3). Temperature, soil moisture content, pH, and type and availability of nitrogen-containing substrates are the main factors affecting the emissions of N_2O (Chang et al., 1998; Rochette et al., 2000; McLain and Martens, 2006; Mosier et al., 2006; Parkin and Kaspar, 2006). The addition of nitrogen to agricultural soils as inorganic fertilizers or OW affects nitrification and denitrification.

The processes involved in the production of CO_2 from organic matter in soil include microbial respiration in the bulk soil and the rhizosphere (Rochette et al., 1999) plus dissolution of carbonates in calcareous soils (Bertrand et al., 2007). In semiarid regions with low rainfall amounts that are restricted to several months in winter and by high temperatures in the summer, soils are typically poor in organic matter. Normally, these soils contribute little to global GHG emissions (McLain and Martens, 2006). However, with irrigation and the addition of fertilizers and OW, these soils can contribute to net CO_2 losses to the atmosphere (Schlesinger, 1999). Soil temperature, soil moisture, soil type, vegetation type, organic substrate type and quantity, and addition of OW can affect the production of CO_2 (Buyanovsky and Wagner, 1983; Johnson et al., 2007). Two important controls on the rate of CO_2 loss from the soil surface are the rate of biological production of CO_2 in the soil profile and gas diffusivity.

Adopting conservation tillage (CT) or no tillage (NT) practices, as well as mulching and integrated nutrient management (including inorganic and organic fertilizers), can reduce GHG emissions. Conventional tillage incorporates fresh plant residues and any OW additions and in doing so exposes the upper soil layer, accelerating the decomposition of organic matter, and increases short- and long-term CO_2 losses compared with CT and NT (Ellert and Janzen, 1999; Curtin et al., 2000; Al-Kaisi and Yin, 2005). Reduced tillage, a term that includes NT and CT with and without the addition of fertilizer and OW, can decrease N_2O emissions (Venterea et al., 2005; Malhi et al., 2006).

Temperature fluctuations and seasonal soil moisture, dominated by rainfall events, affect soil–atmosphere exchange of GHG. Vegetation type (McLain and Martens, 2006) as well as irrigation (Mariko et al., 2007) and other agricultural management practices (Mosier et al., 2006) can be controlled and determine the extent of GHG emissions, particularly in semiarid regions.

The effects of high loads of OW (in particular pasteurized manures by short composting process) on CO_2 and N_2O emissions in a semiarid Mediterranean climate under different tillage practices are not well understood. The objective of the present work was to quantify the effects of management practices on CO_2 and N_2O emissions from pasteurized chicken manure (PCM)-treated in comparison to CR-amended and no residue (NR) soils and to relate emission rates to environmental factors.

Materials and Methods

Experimental Design

A 3-yr field experiment was initiated in December 2004 at the Volcani Center in Bet Dagan, Israel. The soil at the site is a sandy loam (Typic rhodoxeralf). The surface soil (0–10 cm) properties include: 17.5% clay, 2.5% silt, and 80% sand; a CEC of 16 cmol kg^{-1}; 10.3 g kg^{-1} organic C; a C/N ratio of 10.3; a $pH_{(H2O)}$ of 7.3; and $CaCO_3$ <10 g kg^{-1}.

The experiment consisted of a total of nine treatments. Three main treatments were: no tillage (NT) and shallow tillage by disking to about 10 cm once a year immediately after residue addition (ST) with sweet corn crop or ST without a crop (ST–no crop). Each main practice was amended with CR, PCM, or NR. Treatments were set up randomly in six blocks of 2 × 5 m plots (total of 54 plots). One crop of sweet corn (*Zea mays* L.) ("Royalty") was grown each year (April–July) on all except the ST–no crop plots. The field was drip irrigated, and the plots with corn were irrigated according to pan evaporation values and plant growth stage. A minimum irrigation of 1 mm d^{-1} was applied to ST–no crop plots to maintain constant soil moisture. Fertilizers (N, P, K, and microelements) were applied to corn plots via the irrigation system to meet crop demand throughout the growing season. Total fertilizer in a growing season was 240 kg N ha^{-1}, 320 kg K ha^{-1}, and 40 kg P ha^{-1}.

Corn residue (stover only) was collected at the end of each growing season, air-dried, shredded, and returned to the field plots. Pasteurized chicken manure was brought each year from a plant in Mazkeret Batya, Israel, where it had undergone aerobic fermentation at 70°C for 48 h. The N and C contents of the PCM and quantities of the N and C applied are shown in Table 1. Mean mineral N in PCM, in the form of NH_4 only (the amount of NO_3 was negligible), was 4700 mg kg^{-1} (wet weight). The total amount applied was 40 Mg ha^{-1} (wet weight), corresponding to common additions of compost by organic farmers in Israel (Zeevi, 2008). This is higher than typical compost application in organic agriculture in California, which is in the range of 11.2 to 22.4 Mg ha^{-1} (wet weight)

Table 1. Composition of corn residues and pasteurized chicken manure applied to the experimental plots.

Residue	Growing year	TC†	TN	Applied C	Applied N	Application date	Incorporation date
		g kg^{-1}		kg ha^{-1}			
CR‡	2005	390	10.1	2,184	56	2 Dec. 2004	12 Jan. 2005
CR	2006	444	17.0	1,838	70	30 Nov. 2005	5 Dec. 2005
CR	2007	410	12.6	1,627	50	20 Dec. 2006	26 Dec. 2006
CR	2008	458	19.3	1,695	71	23 Dec. 2007	26 Dec. 2007
PCM	2005	362	39.0	10,150	1090	12 Jan. 2005	12 Jan. 2005
PCM	2006	380	47.5	10,640	1230	28 Nov. 2005	5 Dec. 2005
PCM	2007	406	43.2	9,419	1002	20 Dec. 2006	26 Dec. 2006
PCM	2008	380	45.2	10,420	1240	23 Dec. 2007	26 Dec. 2007

† TC, total C; TN, total N.

‡ CR, corn residues; PCM, pasteurized chicken manure.

(Gaskell et al., 2007). Such quantities are applied when excess agricultural and domestic OW is produced and there are no other local alternatives for recycling. Assuming typical N mineralization for composts of 15 to 20% of total N (Hadas and Portnoy, 1997), the amount of PCM applied was expected to supply 150 to 200 kg ha^{-1} of N to the corn crop in the first year after application. The residues were applied, and shallow tillage for ST treatments was performed about 4 mo before planting. Soil temperature was measured using TMC6-HD sensors installed 1, 5, 10, and 20 cm below ground and connected to a data logger. Soil moisture content was measured with a neutron-scattering apparatus (Hydroprobe model 503DR; CPN, Martinez, CA).

Soil Samples

Soil samples were taken before and several times during the growing season from depths of 0 to 10 and 10 to 30 cm. Samples were air-dried and extracted with 1 mol L^{-1} KCl (1:5, w/w) for ammonium and nitrate (Hadas et al., 2004, following Keeney and Nelson, 1982), which were analyzed with an autoanalyzer (Lachat Instruments, Milwaukee, WI). The procedure of drying soil samples before extracting the inorganic N was used for obtaining highly homogenized samples that represent the bulk soil. However, an increase of inorganic N may occur due to stimulation of mineralization as a result of drying (Ma et al., 2005).

Residue Analysis

Samples of PCM were taken when brought to the field, dried at 40°C, and ground to powder. Plants were sampled at the end of the growing season, dried at 60°C, and ground to pass a 20-mesh sieve. Plant material (20 mg) and powdered PCM (10 mg) were analyzed for total C (TC) and total N (TN) using an NC soil analyzer (Flash EA 1112 series; Thermo Finnigan, Milan, Italy).

Gas Flux Measurements

Flux measurements of CO_2 and N_2O were performed from December 2005 through February 2008. Gas flux from the soil surface was determined by measuring the increase in concentration during 1 h in a closed cylinder covering the soil. Polyvinyl chloride rings (15 cm diameter and 10 cm height) were inserted 8 cm into the soil in three out of six replicate plots (three blocks) of each treatment (Hutchinson and Mosier, 1981). In the case of plots with plants, the bases were installed between rows during the growing season, and drip pipes were placed over the bases to maintain soil moisture equal to that of the surroundings. Bases remained in the soil for the entire experiment and were removed and reinserted only in plots where incorporation of residues was required. The PVC sample chamber cap had a vent needle and butyl rubber stopper used as a port for air sample withdrawal. Some caps contained a port with a rubber stopper where thermometers were inserted to measure air temperature inside the chamber during the sampling period. The dimensions of the PVC chamber are: 7.0 cm height above ground, 15.0 cm inner diameter, and 1230 cm^3 volume. Before measurements, caps were put onto the rings and sealed with silicone grease (Silicaid 1010; Aidchim Ltd., Israel). Chamber gas samples were collected at regular intervals of 0, 30, and 60 min by inserting the needle of a polypropylene syringe through a septum in the chamber top and slowly withdrawing 12 mL of gas. Samples were immediately transferred to 9-mL glass vials sealed with a butyl rubber septum (Alltech, Deerfield, IL). Gas samples were analyzed within 1 wk after sampling using gas chromatography (GC) with a headspace autosampler (Teledyne Tekmar, Mason, OH). As previously described by Venterea et al. (2005), the GC system (HP 5890; Hewlett-Packard, Palo Alto, CA) incorporated two detectors: a thermal conductivity detector used for CO_2 determination and an electron capture detector used for N_2O analysis. The GC was calibrated using analytical-grade standards (Scott Specialty Gases, Plumsteadville, PA) (Venterea et al., 2005).

Gas concentrations were converted from μL L^{-1} (volumetric) to concentration (weight) using the following conversion equations based on the ideal gas law and were corrected by using measured air temperature:

$$1\ \mu L\ N_2O\ L^{-1} = 341.2262/(273.15 + T\mathrm{air})\ \mathrm{ng\ N\ cm^{-3}} \qquad [1]$$

$$1\ \mu L\ CO_2\ L^{-1} = 0.1462398/(273.15 + T\mathrm{air})\ \mu\mathrm{g\ C\ cm^{-3}} \qquad [2]$$

where Tair is air temperature (°C).

Fluxes were calculated as the linear relationship between concentrations and time of three consecutive measurements (0, 30, and 60 min) using a total chamber volume of 1230 cm^3. The surface area of covered soil was 176 cm^2. The estimations of daily average gas flux based on the hourly measurements were calculated by using the method of Parkin and Kaspar (2003):

$$\text{Daily average gas flux} = RQ^{(\mathrm{DAT}-T)/10} \qquad [3]$$

where R is the measured gas flux at a specific hour, T is the recorded temperature in the chamber at the time the flux was measured, DAT is the daily average temperature, Q is the Q_{10} factor for CO_2 (1.25) (Parkin and Kaspar, 2003) and for N_2O (3.72) (Parkin and Kaspar, 2006), and daily average gas flux is the resulting estimated mean daily flux based on the single hourly measured flux.

Carbon Dioxide Concentrations

Sets of 2-mm-diam. copper tubes were inserted 10, 20, 30, and 50 cm into the soil in bare plots only. There were four replicate plots for each treatment set in four blocks. The end of the tube was covered with a net, and sand particles were placed at the bottom of the insertion holes to prevent tube clogging. Two tube volumes were withdrawn before sampling, and 2.5-mL air samples were collected and transported to the lab for immediate analysis with an 8610C GC (SRI Instruments, Torrance, CA). Carbon dioxide concentration was monitored at the various depths for 1 yr (February 2007–February 2008).

Statistical Analysis

Air and soil data were subjected to ANOVA with JMP 7.0 software (SAS Institute, 2005), and ANOVA was used to obtain an F value for significance in the five-way linear model, with amendment, cultivation, year, and their interactions and crop and block as main effects. Mean separations were performed on the basis of the Tukey and Kramer honestly significant difference test at p = 0.05. The stepwise regression procedure of JMP 7.0 was used to obtain the best linear equation for the quantitative effects of several independent factors on CO_2 and N_2O emissions from soil.

Results

Air Temperature and Rainfall

The Bet Dagan site is located in a typically Mediterranean climate region, with wet mild winters (November–March) and dry warm summers (June–August). Average minimum daily air temperatures were about 5°C in the winter and about 20°C in the summer. Maximum daily temperatures averaged between 22°C in winter and 32°C in summer (Fig. 1a). Total rainfall was 500, 381, and 413 mm in 2005–2006, 2006–2007, and 2007–2008, respectively, lower than the long-term mean annual rainfall in Bet Dagan (552 mm). In 2005–2006, 63 mm of rain fell from the beginning of the rainy season until residue addition and tillage; in 2006–2007 and 2007–2008, these values were 226 mm and 190 mm, respectively (Fig. 1b). The corn-growing season was from April to July each year.

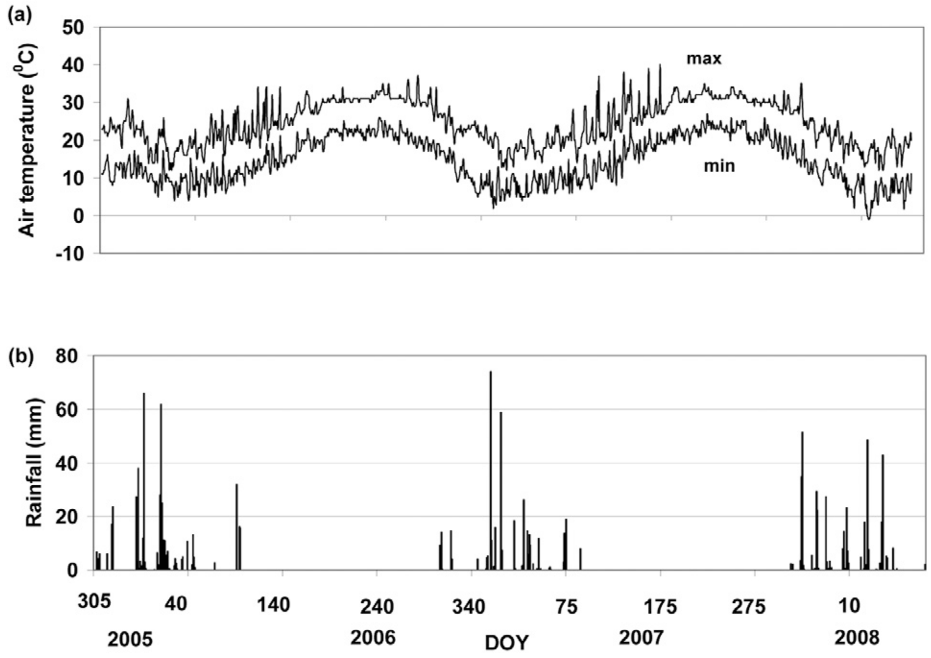

Fig. 1. Daily (a) maximum and minimum air temperatures and (b) rainfall as a function of time at the Bet Dagan field experiment site (Israel Meteorology Services annual reports).

Soil Temperature and Moisture

Daily maximum and minimum temperatures at the 5- and 20-cm depths in the CR plots are shown in Fig. 2. Soil temperatures were not measured in all PCM plots, but when made (data not shown), they showed similar patterns as in the CR plots. No substantial effect of CR incorporation (under ST) on soil temperatures was observed at any time during the observation period; however, in both years, higher maximum temperatures were measured in the no-crop treatments during the growing season and continuing until the end of September (Fig. 2). The minimum temperatures were similar at both depths. Temperature fluctuations around the 33°C mean at 5 cm decreased with depth to 25°C mean at 20 cm, as did the differences between maximum and minimum temperatures. At the 20-cm depth, the maximum temperatures (10–35°C) were more moderate than at the 5-cm depth.

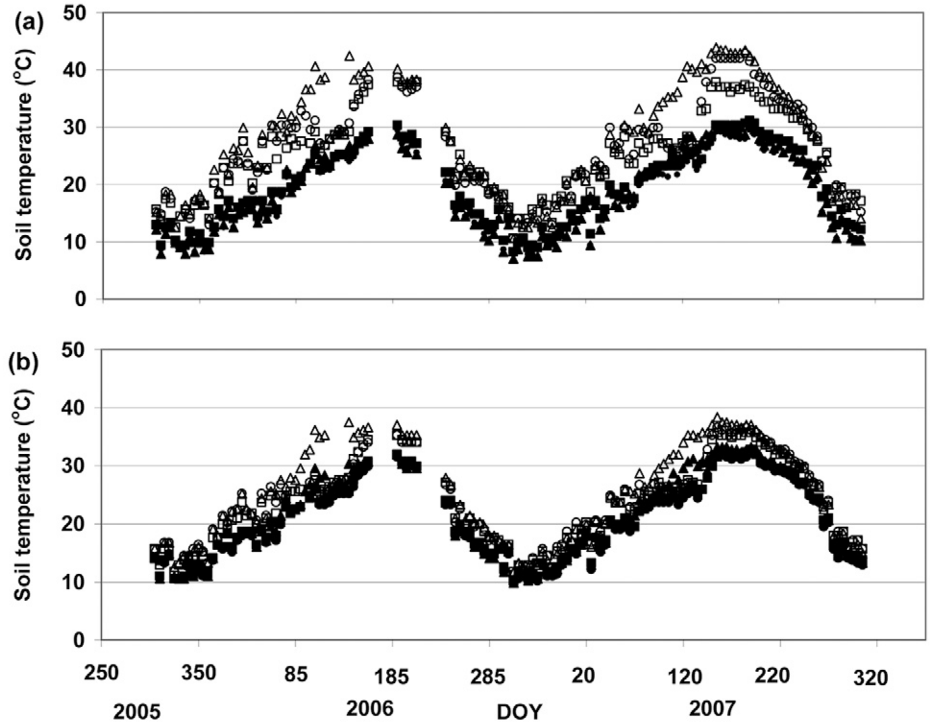

Fig. 2. Soil maximum (open symbols) and minimum (filled symbols) temperatures as a function of time at the Bet Dagan field experiment site at depths of (a) 5 cm and (b) 20 cm in plots with corn residues. NT, no tillage; ST, shallow tillage. Open circles, maximum ST; closed circles, minimum ST; open triangle, maximum ST—no crop; closed triangles, minimum ST—no crop; open squares, maximum NT; closed squares, minimum NT.

Soil moisture content at 10 cm varied with season and irrigation time (Fig. 3). Higher moisture values were obtained from winter (January) until the end of the irrigation period (June), whereas lower values were measured between July and November. During the corn-growing seasons of 2006 and 2007, soil volumetric moisture varied from 10.0 to 16.6% (mean, 14.5%). Significant effects of organic residue application, tillage, and crop on soil volumetric moisture content during the corn-growing seasons were found (Table 2). The mean moisture levels in the PCM- and CR-treated plots were significantly higher (13.5 and 13.8%, respectively) than in the NR plots (12.6%). The NT plots with PCM and CR (i.e., surface application) exhibited significantly higher moisture than the ST plots (13.7 and 13.0%, respectively) (Fig. 3). The plots without crop exhibited significantly higher moisture (13.8%) than plots with corn crop (12.8%) during the corn growing season. When the corn growing season was over and irrigation ceased, we assumed soil moisture content to be unchangeable (values between 9 and 11%) until the beginning of the rainy season.

Carbon Dioxide Flux

Fluxes of CO_2 were measurable all year long (Fig. 4) and exhibited two distinct periods. The first CO_2 peak followed the addition of PCM and CR. The greatest emission was seen after the addition of PCM (Fig. 4c).

The second period of high CO_2 emission was during the growing season when the crop was irrigated (Fig. 4). Tillage increased CO_2 flux except in the PCM treatment, where the fluxes were greatest in the NT plots (Fig. 4c). Lower fluxes (Fig. 4a–4c) were measured in the plots without crop than in those supporting corn crops, regardless of residue treatment, showing the influence of root respiration and root turnover.

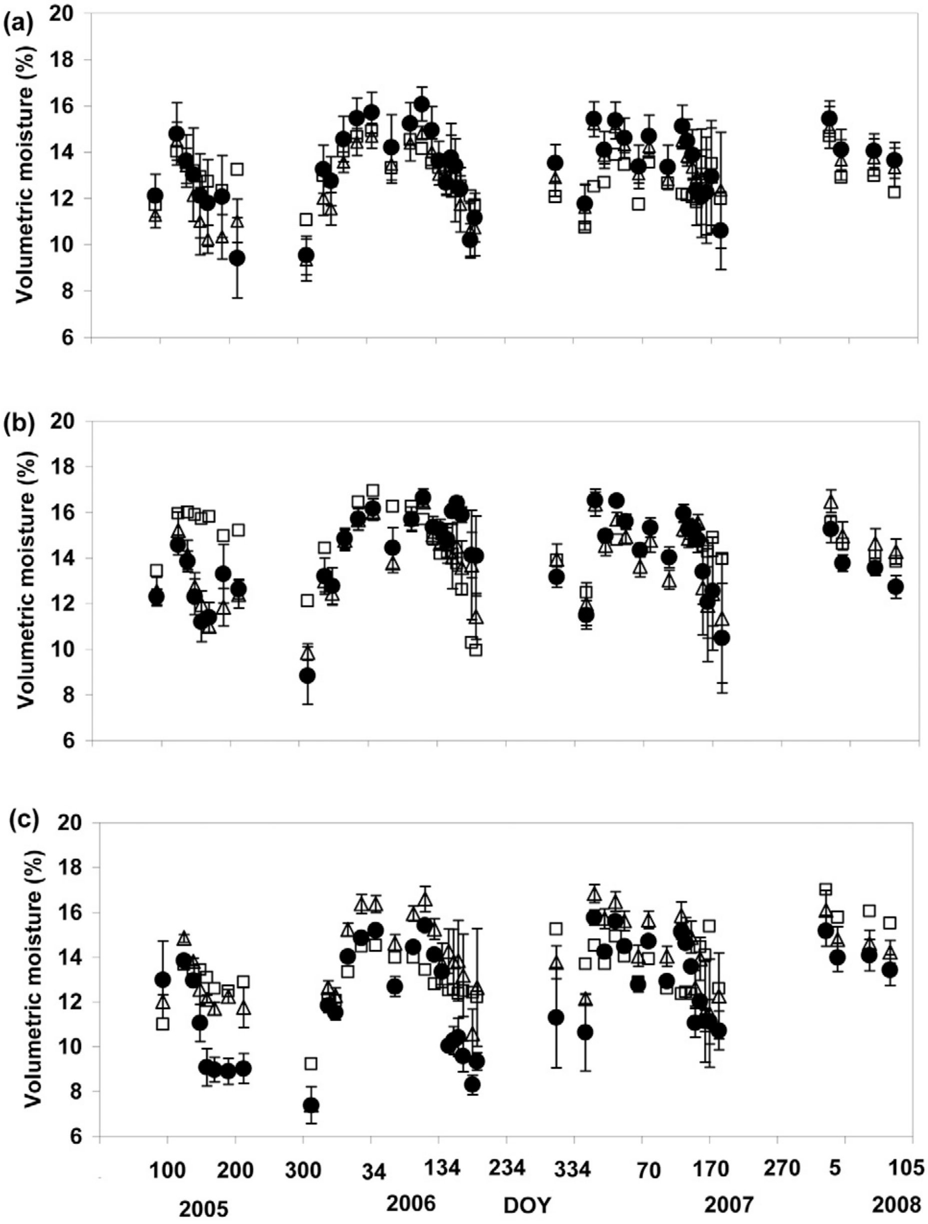

Fig. 3. Seasonal variation in volumetric soil moisture at the Bet Dagan field experiment site at 10 cm depth in (a) no residue, (b) corn residue–amended, and (c) pasteurized chicken manure–amended treatments. NT, no tillage (open squares); ST, shallow tillage (closed circles); ST no crop, shallow tillage without crop (open triangles). Vertical bars represent SD. DOY, day of year.

Seasonal and annual amounts of CO_2–C released to the atmosphere were calculated by summing the product obtained by multiplying the mean CO_2–C values of two sequential measurement dates by the time interval (Table 3). A correction of daily average temperature variation on CO_2 fluxes was made by applying the temperature algorithm (Eq. [3]) proposed by Parkin and Kaspar (2003). This correction reduced the daily flux by 4 to 31% in accordance with values reported by Parkin and Kaspar (2003).

The PCM treatments released more CO_2 than the other treatments during the entire experimental period (Table 3). Annually, and during the corn growing seasons, surface application of amendments in the NT treatment released less CO_2 than their incorporation (ST). On an annual basis, the presence of the corn crop increased the flux significantly (Table 3). For the period from application to corn seeding, the average amounts of C efflux as CO_2 were 6.45, 1.23, and 0.74 Mg ha^{-1} for the PCM, CR, and NR, respectively. Annual amounts of CO_2–C emissions were 9.7, 2.9, and 2.3 Mg ha^{-1} for the PCM, CR, and NR, respectively (Table 3). Comparison of the efflux with and without a corn crop during the growing season shows that root respiration and root turnover by the corn accounts for a mean annual efflux of 1.25 Mg C ha^{-1} (Table 3)

Carbon Dioxide Concentration in the Soil Profile

The CO_2 concentration in the soil atmosphere was determined on a weekly basis for 1 yr (February 2007–February 2008) in ST-without crop plots (Fig. 5; data are shown for the 10- and 50-cm depths). The CO_2 concentrations in PCM plot profiles were higher than for the other treatments even at the depth of 50 cm and for over 6 mo after application of amendments. In all treatments, concentrations increased with soil depth (10–50

Table 2. Effect of residue application and cultivation practice on mean soil water content through three corn-growing seasons.

Treatment	df	θ
		%, volumetric
Amendment		
PCM†		13.53a‡
CR		13.84a
NR		12.63b
Cultivation		
NT		13.70a
ST		12.97b
Crop		
No crop		13.84a
Corn crop		12.83b
F significance		
Block	5	0.0224
Amendment	2	0.0001
Cultivation	1	0.0023
Crop	1	<0.0001
Date	14	<0.0001
Amendment × cultivation	2	<0.0001
Amendment × crop	2	0.0002
Amendment × date	28	0.7618
Cultivation × date	14	0.9974
Crop × date	14	0.0019

† CR, corn residues; NR, no residue; NT, no tillage; PCM, pasteurized chicken manure; ST, shallow tillage.

‡ Following mean separation by Tukey-Kramer's HSD test, values within a column followed by different letters are significantly different at the $p = 0.05$ level of probability.

cm). Measurements began in winter when water content in the soil profile was high. A decrease in CO_2 concentrations was seen after the end of the rainy season (March and April) as the soils became drier. During the corn-growing season, the concentrations increased because the ST-without crop plots received irrigation to maintain the same moisture as in plots with corn plants. When the corn-growing season was over and irrigation ceased, CO_2 concentrations decreased in the soil profile, especially at depth. At the end of the year, rainfall induced another increase in concentration.

Nitrous Oxide Flux

Nitrous oxide emissions exhibited the same seasonal pattern as CO_2 throughout the experiment, but the ratio between the emissions during the first peak in the dormant season to the second peak during the growing season was much larger (Fig. 6; Table 4). Also, the ratio of the emission from the PCM treatment to the other treatments was much higher than for CO_2. The highest observed flux was 294 g N ha^{-1} h^{-1} following the rains after incorporation of PCM (Fig. 1b and 6c). The highest emission in CR treatments was about 3.5 g N ha^{-1} h^{-1}, also measured following the rains after residue application and during the corn-growing season. In the plots without crop, the highest fluxes were recorded after a week of heavy rainfall in the second year (2006–2007), with NT plots showing lower values than tilled plots (Fig. 1 and 6).

In the CR treatments, the flux from the plots without crop was lower than from the plots with corn, suggesting that root turnover was supplying energy for denitrification (Fig. 6). The opposite effect was observed in the PCM plots, where the plots with corn plants had lower N_2O fluxes than the ST-without crop plots because of the decrease in soil NO_3 due to N uptake by plants. Tillage also affected the emission of N_2O; in the PCM NT plots, the flux of N_2O (up to 15 g N ha^{-1} h^{-1}) was greater than from ST plots. However, in the CR plots with corn, the NT treatment had lower N_2O emissions than the ST plot. In the CR treatments, the plots without corn plants had lower N_2O emissions than the ST plots with corn.

Similar to CO_2, annual emission of N_2O was greatest in the PCM treatment (34.4 kg ha^{-1} compared with 0.94 and 0.77 kg ha^{-1} in the CR and NR treatments, respectively) (Table 4). In all treatments, a very high fraction of the total annual emission occurred in the winter months following the rain after residue application and cultivation. This accounted for 90% of the flux from the PCM treatment and 55% for both the CR and NR treatments. In the growing season, the emission from the PCM was also higher than in the two other treatments, but the difference between the other two residue treatments was smaller and CR did not differ significantly from NR. Tillage significantly increased annual N_2O fluxes but not during the corn-growing season (Table 4).

Inorganic Nitrogen Concentrations in Soil

Higher inorganic N (NH_4 + NO_3) concentrations were determined at the 0- to 10-and 10- to 30-cm depths in PCM plots than in the CR and NR plots (Fig. 7). Inorganic N concentrations in the CR plots were similar to the NR plots. Of the PCM-treated plots, inorganic N concentrations were higher in the ST cultivation practices (Fig. 7a and 7b) than in the NT plots (Fig. 7c and 7d), especially in the winter rainy season after application and incorporation of residues. During the corn-growing seasons, mineral N concentration increased as a result of N fertilization and decreased at the end of the season due to uptake by plants. Regardless of tillage, exceptionally high mineral N concentrations were observed in PCM plots on 1 Jan. 2007, a few days after application and after a week of abundant rainfall (104 mm). After application of PCM and tillage, there was a residual effect of organic residue mineralization up until as late as March. In most cases, in the PCM plots, the concentration at the 10- to 30-cm depth was half that at the 0- to 10-cm depth, probably because of shallow incorporation and continued production of mineral N in excess of the downward transport by rainfall.

Discussion

Dependence of Carbon Dioxide and Nitrous Oxide Fluxes on Soil Condition and Management Parameters

Stepwise regression showed that the dominant factor that explained about 39 and 40% of the variability in CO_2 and N_2O fluxes was the concentration of NH_4 in soil solution (Tables 5 and 6). Nitrous oxide emissions result from the microbial processes of nitrification and denitrification. The relation between N_2O fluxes and soil solution NH_4 occurred because NH_4 is the reactant in the nitrification process that produces NO_3, and NO_3 is required for denitrification. The ammonium-rich PCM

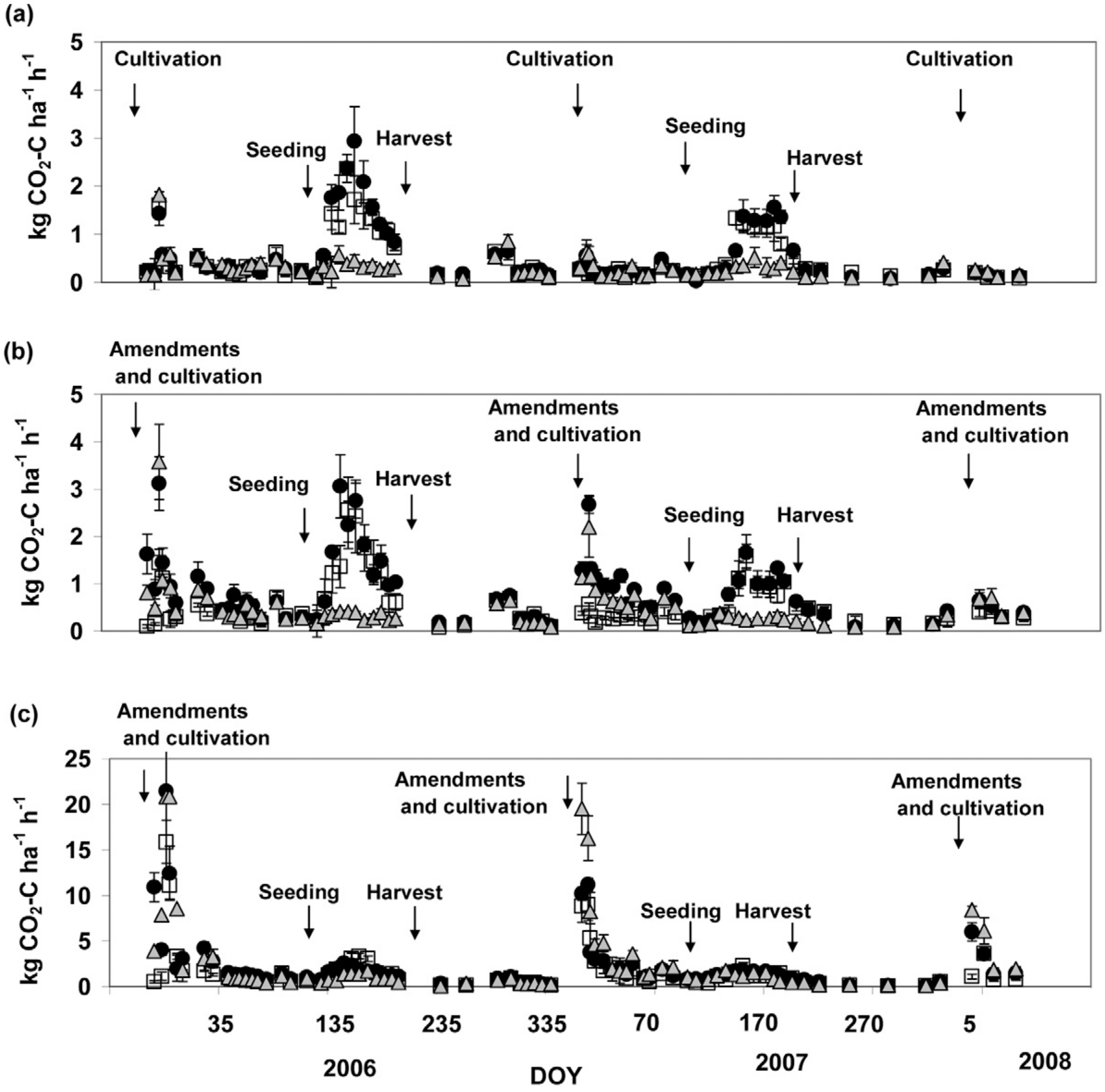

Fig. 4. Seasonal variation in CO_2 fluxes (kg CO_2–C ha^{-1} h^{-1}) at the Bet Dagan field experiment site in (a) no-residue (NR), (b) corn residue-amended (CR), and (c) pasteurized chicken manure–amended (PCM) plots. NT, no tillage (open squares); ST, shallow tillage (closed circles); ST no crop, shallow tillage without crop (open triangles). Vertical bars represent SD. Note the difference in scale for panel (c).

was substrate for the ammonium-oxidizing bacteria responsible for N_2O production through nitrification (Tortoso and Hutchinson, 1990). Nitrate was the dominant inorganic N ion in most of our measurements; therefore, Fig. 7, which presents the inorganic N (the sum of NH_4 and NO_3), is very similar to a figure that presents NO_3 alone (not presented). The exceptions are the samples from the PCM treatments in the winter (January 2006, 2007, and 2008) in the upper soil layer. In the PCM treatments, the NH_4 percentages were 40, 87, and 68% of total inorganic N in January 2006, January 2007, and January 2008, respectively. The high correlation of N_2O emission with NH_4 rather than inorganic N indicates that the N_2O was produced in the nitrification process. High availability of soluble C in manures in combination with sufficient mineralizable N has also been reported to activate the population of denitrifiers (Johnson et al., 2007).

The strong association of NH_4 concentration in soil solution with CO_2 emissions is probably a result of the relation between labile C in the organic residues and mineralized N. The availability of inorganic N may influence decomposition of organic matter and further CO_2 fluxes when N becomes a limiting factor for microbial activity (Hadas et al., 1998). In the present study, the fertilization with inorganic N after seeding probably enhanced decomposition of SOM and corn residues in the CR and NR treatments.

Time after seeding was the second factor to enter the stepwise regression for fluxes of CO_2 (Table 5). The high fluxes of CO_2 throughout the corn seasons for the plots with corn plants originated from the contribution of root respiration and root turnover, as shown by Chen et al. (2005). During the corn-growing seasons, there was some increase in N_2O flux, but the effect of time after seeding on flux of N_2O did not meet the 0.05 significance level of the stepwise analysis and was not reported. Time after tillage had a significant effect on CO_2 and N_2O fluxes (Tables 5 and 6). The highest peaks of CO_2 and N_2O for all the treatments were observed 2 wk after application of residues and tillage in the first 2 yr and immediately after the application in the third year. In the first 2 yr, the

Table 3. Cumulative emission of carbon dioxide at the experimental plots during the dormant season and during corn-growing periods in 2006 and 2007.

Variable	d	Dormant season (143 d)	Corn season (75 d)	Annual
		———— kg CO_2–C ha^{-1} ————		
Amendment				
PCM†		6446a	2033a	9735a‡
CR		1233b	1068b	2910b
NR		741b	1027b	2318b
Cultivation				
NT		2193b	1272b	4092b
ST		3421a	1480a	5884a
Crop				
Corn crop		2863	2009a	5756a
No crop		2750	743b	4220b
Year				
2006		2795	1452	4946
2007		2818	1300	5030
F significance				
Block	2	0.268	0.692	0.538
Amendment	2	<0.0001	<0.0001	<0.0001
Cultivation	1	<0.0001	0.042	<0.0001
Crop	1	0.664	<0.0001	<0.0001
Year	1	0.932	0.139	0.757
Amendment × cultivation	2	0.001	0.248	0.0001
Amendment × crop	2	0.663	0.014	0.059
Amendment × year	2	0.376	0.853	0.021
Cultivation × year	1	0.090	0.923	0.182
Crop × year	1	0.004	0.001	<0.0001
Amendment × cultivation × year	2	0.022	0.326	0.476
Amendment × crop × year	2	0.0003	0.985	0.0001

† CR, corn residues; NR, no residue; NT, no tillage; PCM, pasteurized chicken manure; ST, shallow tillage.

‡ Following mean separation by Tukey-Kramer's HSD test, values within a column, for each independent variable, followed by different letters are significantly different at the *p* = 0.05 level of probability.

volumetric soil moisture was lower at the time of residue application compared with the third year. The peaks occurred when soil moisture contents rose above 14% (Fig. 3) as a result of rainfall. Flushes of CO_2 and N_2O to the atmosphere occurred after tillage even without the addition of organic amendments, as compared with no tillage. Similar effects of tillage on CO_2 emissions have been reported by Reicosky et al. (1997). Still, surface application of PCM resulted in much higher fluxes than obtained with CR and NR plots. Poultry litter applied on the soil surface under lab conditions has been found to emit high amounts of CO_2 and N_2O within the first 4 d after application (Cabrera et al., 1994). High fluxes following residue addition and tillage (shallow incorporation) are induced by the availability of substrates for microbial activity and mineralization and sufficient soil moisture content. Reicosky et al. (1999) have shown that CO_2 fluxes after residue application are lower from a NT plot than from a plot under conventional tillage: In NT practice, the residues, which are spread over the surface, have less contact with soil particles and maintain a lower soil temperature; therefore, the rate of decomposition is lower.

Carbon dioxide fluxes are also caused by the exposure of deeper soil layers to air as a result of the tillage. Tillage also allows the release of trapped CO_2 from the soil to the atmosphere by breaking the upper layer of soil (Buyanovsky and Wagner, 1983; Ellert and Janzen, 1999). Six et al. (2006) reported that the upper 5-cm soil layer is the most susceptible to the effects of tillage and retains less microbial organic matter when tilled. In most cases in our experiment, NT plots released less N_2O than tilled plots. With PCM additions, the higher flux with tillage could be linked to enhancement of denitrification due to oxygen consumption by the enhanced decomposition of organic matter. In our experiment, residue application and tillage were performed in December of each year, when the rainy season began and the soil was wet enough to allow high microbial activity, resulting in the mineralization of SOM and of added residues. Microbial activity is limited when the soil is dry, even after tillage (Reicosky et al., 1999), and emissions are controlled by soil water regardless of tillage (Lee et al., 2006).

The importance of soil water content and temperature in controlling fluxes of N_2O and CO_2 is linked primarily to the biological nature of C and N transformations. Significant effects of air temperatures on N_2O flux occurred (Table 6), but not on CO_2 fluxes (Table 5). High fluxes of N_2O occurred when the measured volumetric moisture in the soil was between 12 and 16% (58–77% of water-filled pore space). Such values of water content allow the occurrence of both nitrification and denitrification for the production of N_2O (Khalil et al., 2002). Liu et al. (2007) found that N_2O emissions derived from N fertilizer are higher at higher water contents. Significant N_2O release occurred only if there was rainfall immediately after application of inorganic N fertilizer (Jones et al., 2005). Although the N_2O peaks occurred immediately after rainfall, the stepwise regression did not reveal a significant effect of water content on N_2O flux. Unlike N_2O, higher fluxes of CO_2 were correlated with high soil water content. Optimal water contents for biological activity existed in the soil during most of the experiment, except between August and November when irrigation was terminated. An immediate increase in CO_2 flux after irrigation has also been described by Reicosky et al. (1999) and Mariko et al. (2007). The increase seen in our experiment could have been the result of enhanced biological activity or displacement of soil CO_2 by irrigation water.

Carbon dioxide emissions from the soil surface were correlated with the CO_2 concentration gradients in the soil atmosphere according to the following relationship:

$$Y = 0.11X + 0.106 \quad r^2 = 0.49 \quad p(F)\ X < 0.0001 \qquad [4]$$

where Y is CO_2–C flux (kg ha^{-1} h^{-1}) and X is the gradient of CO_2 in the soil atmosphere (mL L^{-1}) between 50 and 10 cm

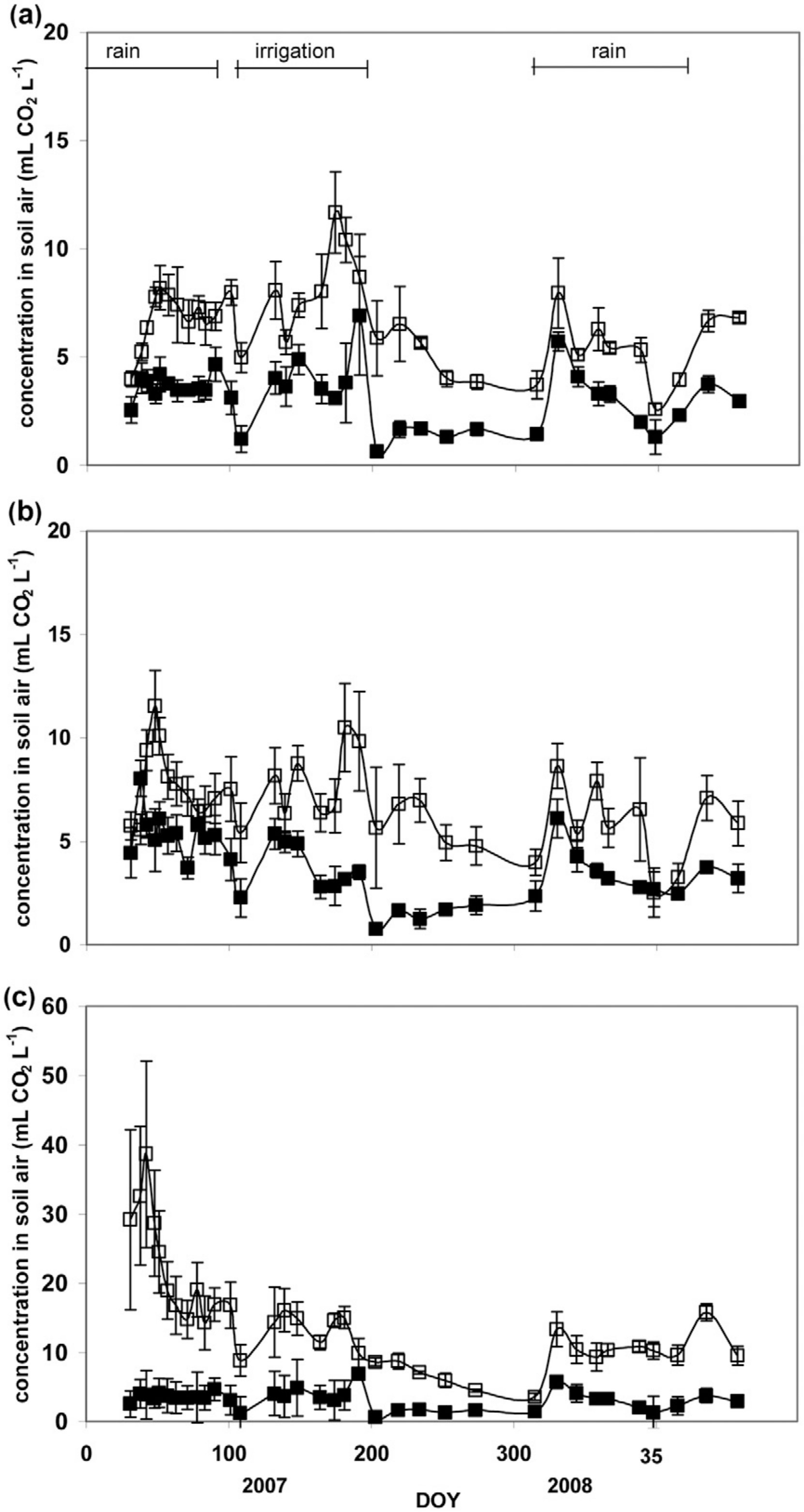

Fig. 5. Concentration of CO_2 in soil air in (a) bare plots with no residue (NR), (b) plots amended with corn residue (CR), and (c) plots amended with pasteurized chicken manure (PCM). Soil air was monitored at depths of 10 cm (closed squares) and 50 cm (open squares). Vertical bars represent SD. Note the difference in scale for panel (c).

depth (CO_2 fluxes to the atmosphere and concentrations of CO_2 in soil were measured in the same plots within less than 6 d). Concentrations of CO_2 in soil and emissions from soil are related to soil temperature and percentage of soil water content. Buyanovsky and Wagner (1983) found the combination of soil moisture and temperature to be responsible for more than 50% of CO_2 emission fluctuations. In the present work, CO_2 concentrations were measured in ST-without crop plots only, which received minimal irrigation in corn-growing season; therefore, the combined effects of CO_2 concentrations in soil atmosphere and soil moisture on CO_2 emissions could not be examined.

Carbon Budget of Amended Plots

The calculated annual emission CO_2–C was 9.7 Mg ha^{-1} for PCM (Table 3), including an average of 2.0 Mg C ha^{-1} yr^{-1} emitted during the corn cropping seasons. Jones et al. (2006) reported the amount of 13.7 Mg C ha^{-1} yr^{-1} emitted from plots with poultry manure (16.8 Mg C ha^{-1} applied yearly in two equal portions). A much lower value of 4.0 Mg C ha^{-1} yr^{-1} was reported by Ding et al. (2007) for cultivated land that had received 2.7 Mg ha^{-1} (dry mass basis) composted manure for 13 yr. Annual estimates of CO_2 fluxes from tilled and nontilled corn plots, without additional organic residues, were made by Wagai et al. (1998), generating values of 5.08 and 5.34 Mg C ha^{-1} yr^{-1}, respectively.

If we deduct the amount of CO_2–C emitted from soil without any organic addition (2.3 Mg C ha^{-1} yr^{-1}) from that emitted in the PCM treatment (9.7 Mg C ha^{-1} yr^{-1}), a net amount of 7.4 Mg C ha^{-1} yr^{-1} is presumed to be the result of PCM application. The amount of C applied yearly as PCM averaged 10 Mg ha^{-1}. A large amount (74%) of the applied C was emitted as CO_2–C each year from plots with PCM. However, during the cropping season, the gap between PCM and the no-crop treatment was 1.0 Mg ha^{-1} yr^{-1}. The growth rate and production of aboveground biomass was much higher with PCM than in the other two treatments (data not shown). The excess CO_2–C emission from the PCM treatment during the cropping season is due to root respiration and root turnover. Thus, a net amount of 7.4 − 1.0 = 6.4 Mg C ha^{-1} yr^{-1} is presumably the result of PCM application, reducing the percentage of emitted C to 64% of that applied. These results indicate the rapid decomposition of manure under field conditions in a semiarid Mediterranean climate with an irrigated summer crop. Being an unstable residue, PCM exhibited a high mineralization rate similar to the data reported by Jones et al. (2006), who observed no residual fluxes 1 yr after poultry manure addition and before the following year's addition. The potential yearly contribution of applied manure to SOM enrichment in the upper 10 cm is 0.25%, assuming that 36% of the PCM-C remained in soil.

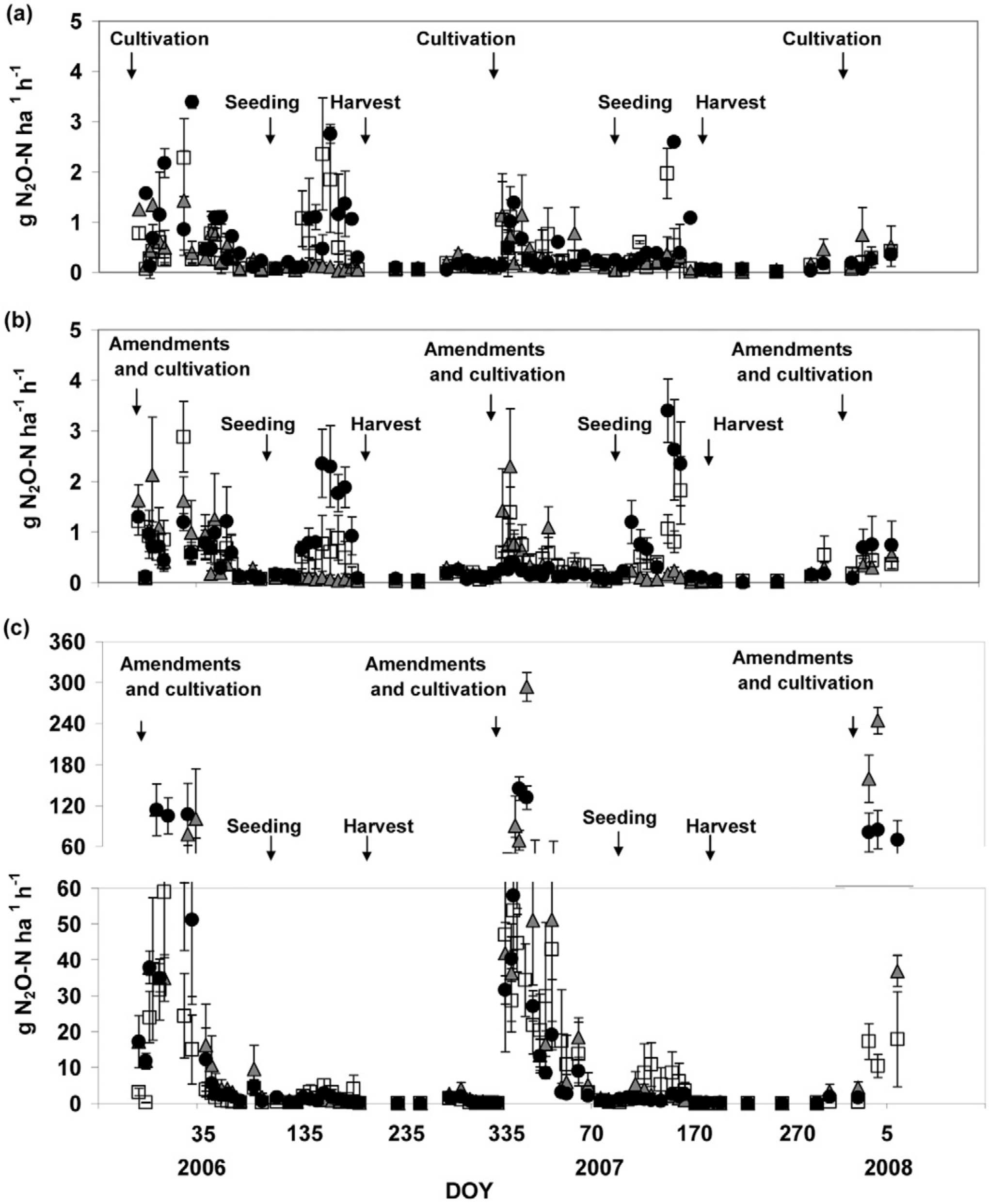

Fig. 6. Seasonal variation in N_2O emission (g N_2O–N ha^{-1} h^{-1}) at the Bet Dagan field experimental site in (a) no-residue (NR), (b) corn residue–amended (CR), and (c) pasteurized chicken manure–amended (PCM) plots. NT, no tillage (open squares); ST, shallow tillage (closed circles); ST no crop, shallow tillage without crop (open triangles). Vertical bars represent SD. Note the difference in scale for panel (c).

Prolonged and continual PCM application will probably have an effect on SOM.

Annual Emission of Nitrous Oxide

The N_2O data, after adjustment with the Parkin and Kaspar (2006) temperature correction algorithm, showed that 34.4 kg N ha^{-1} yr^{-1} of the 1000 to 1230 kg N ha^{-1} yr^{-1} added as PCM was evolved as N_2O, compared with only 0.94 and 0.77 kg ha^{-1} yr^{-1} from the CR and NR, respectively. Chang et al. (1998) reported high N_2O emissions from long-term manured soils of up to 56 kg N ha^{-1} yr^{-1} for a 180 Mg ha^{-1} manure rate treatment. Although the annual emission of N_2O from PCM plots was high, it is just 3% of the total N applied with PCM. Jones et al. (2005) reported that 0.5 to 2.6% of N applied with poultry manure (32–54 kg N ha^{-1}) was evolved as N_2O.

Conclusions

The data collected during this 3-yr field experiment showed that CO_2 and N_2O emissions from residue-amended soils were affected by climatic and management factors. The total annual amount of CO_2 emission that can be attributed to PCM treatment was high (64% of the organic C applied). Consequently, soil amendment with nonstabilized poultry manure (PCM) to field crops in the Mediterranean region during the winter (rainfall season) results in a build-up of soil C stocks only with long-term use. Considerable emissions of N_2O (mean, 34.4 kg N ha^{-1} yr^{-1}) were measured in the PCM treatment. These elevated N_2O emissions not only represent a loss of plant-available N, but, given the long atmospheric residence time and global warming potential of N_2O (296 times that of CO_2), they are also important from a global climate point of view.

Carbon dioxide and N_2O fluxes were well correlated with soil NH_4 concentrations and with days since tillage and days since seeding. Carbon dioxide fluxes were correlated with soil water content, whereas N_2O fluxes were most affected by air temperature.

Results also showed an enhancement in annual emissions of both gases with shallow tillage. The presence of a crop during the growing season contributed to CO_2 fluxes but did not have a measureable effect on N_2O fluxes. Controllable factors, such as type of residue and tillage, time of application, and management of crops, could be key factors to reducing GHG emissions in semiarid regions.

Table 4. Cumulative emission of nitrogen oxide at the experimental plots during the dormant season and during corn-growing periods in 2006 and 2007.

Variable	df	Dormant season (143 days)	Corn season (75 days)	Annual
		kg N_2O–N ha^{-1}		
Amendment				
PCM†		30.8a‡	1.20a	34.4a
CR		0.5b	0.39b	0.9b
NR		0.4b	0.27b	0.8b
Cultivation				
NT		6.4b	0.84	7.3b
ST		14.7a	0.55	15.4a
Crop				
Corn crop		10.1b	0.78a	11.0b
No crop		16.1a	0.36b	16.7a
Year				
2006		11.6	0.63	14.2
2007		10.8	0.65	11.4
F significance				
Block	2	0.337	0.368	0.340
Amendment	2	<0.0001	<0.0001	<0.0001
Cultivation	1	0.040	0.218	0.046
Crop	1	0.030	0.007	0.045
Year	1	0.561	0.355	0.575
Amendment × cultivation	2	0.017	0.001	0.034
Amendment × crop	2	0.011	0.073	0.008
Amendment × year	2	0.790	0.008	0.840
Cultivation × year	1	0.108	0.943	0.109
Crop × year	1	0.856	0.017	0.916
Amendment × cultivation × year	2	0.085	0.956	0.096
Amendment × crop × year	2	0.950	0.768	0.948

† CR, corn residues; NR, no residue; NT, no tillage; PCM, pasteurized chicken manure; ST, shallow tillage.

‡ Following mean separation by Tukey-Kramer's HSD test, values within a column, for each independent variable, followed by different letters are significantly different at the $p = 0.05$ level of probability.

Acknowledgments

This research was supported by Research Grant Award No. IS-3517-04 from BARD, The United States-Israel Binational Agricultural Research and Development Fund. We thank Mr. Tibor Markowitz for his significant contribution in setting the field experiment and performing soil moisture measurements.

References

Al-Kaisi, M.M., and X. Yin. 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations. J. Environ. Qual. 34:437–445.

Bertrand, B., O. Delfose, and B. Mary. 2007. Carbon and nitrogen mineralization in acidic, limed and calcareous agricultural soils: Apparent and actual effects. Soil Biol. Biochem. 39:276–288.

Buyanovsky, G.A., and G.H. Wagner. 1983. Annual cycles of carbon dioxide level in soil air. Soil Sci. Soc. Am. J. 47:1139–1145.

Cabrera, M.L., S.C. Chiang, W.C. Merka, O.C. Pancorbo, and S.A. Thompson. 1994. Pelletizing and soil water effects on gaseous emissions from surface-applied poultry litter. Soil Sci. Soc. Am. J. 58:807–811.

Chang, C., C.M. Cho, and H.H. Janzen. 1998. Nitrous oxide emissions from long-term manured soils. Soil Sci. Soc. Am. J. 62:677–682.

Chen, D., J.A.E. Molina, C.E. Clapp, R.T. Venterea, and A.J. Palazzo. 2005. Corn root influence on automated measurement of soil carbon dioxide concentrations. Soil Sci. 170:779–787.

Curtin, D., H. Wang, F. Selles, B.G. McConkey, and C.A. Campbell. 2000. Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotation. Soil Sci. Soc. Am. J. 64:2080–2086.

Ding, W., L. Meng, Y. Yin, Z. Cai, and X. Zheng. 2007. CO_2 emission in an intensively cultivated loam as affected by long term application of organic manure and nitrogen fertilizer. Soil Biol. Biochem. 39:669–679.

Ellert, B.H., and H.H. Janzen. 1999. Short-term influence of tillage on CO_2 fluxes from a semi-arid soil on the Canadian Prairies. Soil Tillage Res. 50:21–32.

Gaskell, M., R. Smith, J. Mitchell, S.T. Koike, C. Fouche, T. Hartz, W. Horwath, and L. Jackson. 2007. Soil fertility management for organic crops. Available at http://anrcatalog.ucdavis.edu (verified 2 Jan. 2010). Publ. 7249. Univ. of California, Division of Agriculture and Natural Resources, Davis, CA.

Hadas, A., and R. Portnoy. 1997. Rates of decomposition in soil and release of available nitrogen from cattle manure and municipal waste composts. Compost Sci. Util. 5:48–54.

Hadas, A., T.B. Parkin, and P.D. Stahl. 1998. Reduced CO_2 release from decomposing wheat straw under N-limiting conditions: Simulation of carbon turnover. Eur. J. Soil Sci. 49:487–494.

Hadas, A., M. Agassi, H. Zhevelev, L. Kautsky, G.J. Levy, E. Fizik, and M. Gotessman. 2004. Mulching with composted municipal solid wastes in the Central Negev, Israel. II. Effect on available nitrogen and phosphorus and on organic matter in soil. Soil Tillage Res. 78:115–128.

Hutchinson, G.L., and A.R. Mosier. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45:311–316.

IPCC. 2007. Causes of change. p. 36–41. *In* Climate change 2007: Synthesis report. Topic 2. Intergovernmental Panel on Climate Change, Valencia, Spain.

Johnson, J.M.F., A.J. Franzluebbers, S. Lachnicht Weyers, and D.C. Reicosky. 2007. Agricultural opportunities to mitigate greenhouse gas emissions. Environ. Pollut. 150:107–124.

Jones, S.K., R.M. Rees, U.M. Skiba, and B.C. Ball. 2005. Greenhouse gas emissions from a managed grassland. Global Planet. Change 47:201–211.

Jones, S.K., R.M. Rees, D. Kosmas, B.C. Ball, and U.M. Skiba. 2006. Carbon sequestration in a temperate grassland; management and climatic controls. Soil Use Manage. 22:132–142.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen—inorganic forms. p. 643–698. *In* A.L. Page, R.H. Miller, and D.R. Keeney (ed.) Methods of soil analysis. Part 2. Chemical and microbiological properties, 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Khalil, M.I., A.B. Rosemnani, O. Van Cleemput, C.I. Fauziah, and J. Shamshuddin. 2002. Nitrous oxide emissions from an Ultisol of the humid tropics under maize-groundnut rotation. J. Environ. Qual. 31:1071–1078.

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

Liu, X.J., A.R. Mosier, A.D. Halvorson, C.A. Reule, and F.S. Zhang. 2007. Dinitrogen and N_2O emissions in arable soils: Effect of tillage, N source, and soil moisture. Soil Biol. Biochem. 39:2362–2370.

Ma, B.L., J. Ying, and D. Balchin. 2005. Impact of sample preservation methods on the extraction of inorganic nitrogen by potassium chloride. J.

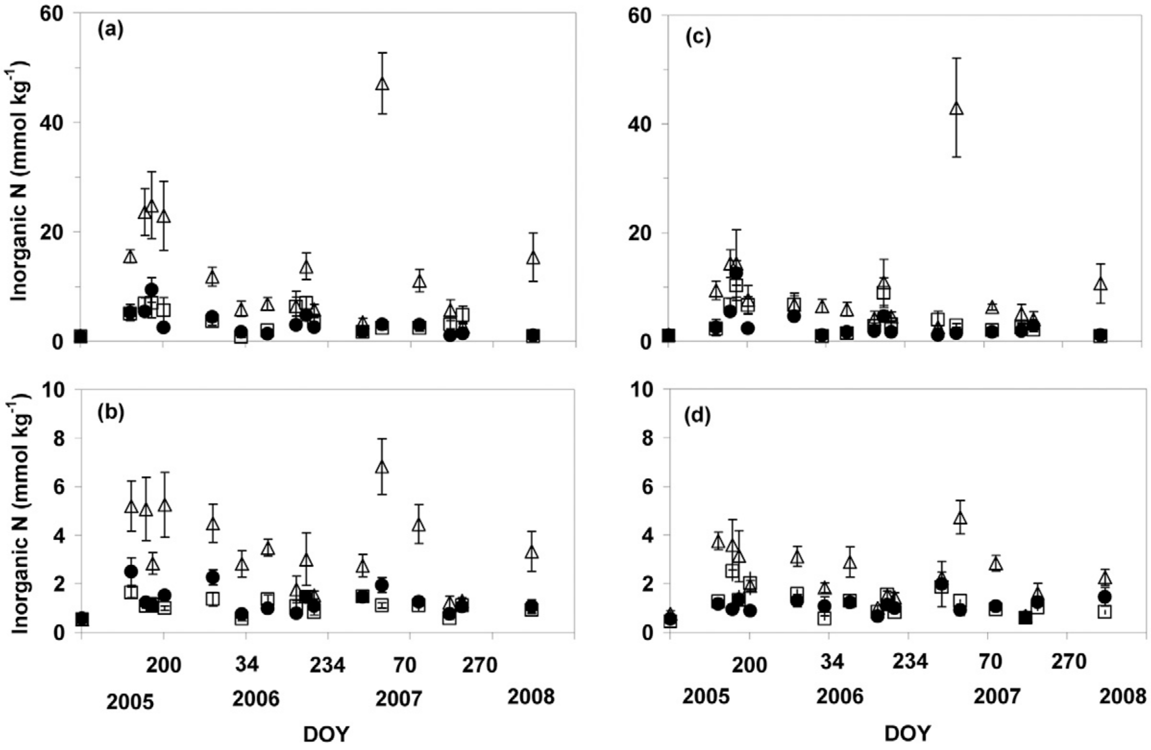

Fig. 7. Seasonal variation of inorganic N in the soil profile at the Bet Dagan field experiment site in plots with corn crop under shallow tillage (ST) in (a) 0 to 10 cm and (b) 10 to 30 cm and no tillage (NT) in (c) 0 to 10 cm and (d) 10 to 30 cm. CR, corn residue–amended (open squares); NR, no residue (closed circles); PCM, pasteurized chicken manure–amended plots (open triangles). Vertical bars represent SD.

Table 5. Analysis of the relation between carbon dioxide flux and soil parameters/management factors using stepwise regression fit.

Step	Parameter†	Coefficient	*P* value	R^2
1	C_{NH4}	44.74	<0.0001	0.388
2	$T_{seeding}$	17.14	<0.0001	0.453
3	$T_{tillage}$	5.90	0.0004	0.483
4	θ^2	5.89	0.1581	0.487
5	θ	4.14	0.0532	0.496

† C_{NH4}, NH_4–N concentration in soil (mg kg^{-1}); $T_{seeding}$, time after seeding (days); $T_{tillage}$, time after tillage (days); θ, soil water content (%, volumetric).

Table 6. Analysis of the relation between nitrous oxide flux and soil parameters and management factors using stepwise regression fit

Step	Parameter	Coefficient	*P* value	R^2
1	C_{NH4}†	30.65	<0.0001	0.402
2	$T_{tillage}$	11.81	<0.0001	0.450
3	$Temp_{max}$	9.37	0.0383	0.460
4	$Temp_{max}^{\ 2}$	5.57	0.0170	0.473

† C_{NH4}, NH_4–N concentration in soil (mg kg^{-1}); $T_{tillage}$, time after tillage (days); $Temp_{max}$, air temperature (°C).

Plant Nutr. 28:785–796.

Malhi, S.S., R. Lemke, Z.H. Wang, and B.S. Chhabra. 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. Soil Tillage Res. 90:171–183.

Mariko, S., T. Urano, and J. Asanuma. 2007. Effects of irrigation on CO_2 and CH_4 fluxes from Mongolian steppe soil. J. Hydrol. 333:118–123.

McLain, J.E.T., and D.A. Martens. 2006. Moisture controls on trace gas fluxes in semiarid riparian soils. Soil Sci. Soc. Am. J. 70:367–377.

Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 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., and T.C. Kaspar. 2003. Temperature controls on diurnal carbon dioxide flux: Implications for estimating soil carbon loss. Soil Sci. Soc. Am. J. 63:1763–1772.

Parkin, T.B., and T.C. Kaspar. 2006. Nitrous oxide emissions from corn-soybean systems in the Midwest. J. Environ. Qual. 35:1496–1506.

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

Reicosky, D.C., D.W. Reeves, S.A. Prior, G.B. Runion, H.H. Rogers, and R.L. Raper. 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil Tillage Res. 52:153–165.

Rochette, P., L.B. Flanagen, and E.G. Gregorich. 1999. Separating soil respiration into plant and soil components using analysis of the natural abundance of carbon-13. Soil Sci. Soc. Am. J. 63:1207–1213.

Rochette, P., E. van Bochove, D. Prevost, D.A. Angers, D. Cote, and N. Bertrand. 2000. Soil carbon and nitrogen dynamics following application of pig slurry for the 19th consecutive year: II. Nitrous oxide fluxes and mineral nitrogen. Soil Sci. Soc. Am. J. 64:1396–1403.

SAS Institute. 2005. SAS user's guide: Statistics. SAS Inst., Cary, NC.

Six, J., S.D. Frey, R.K. Thiet, and K.M. Batten. 2006. Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Sci. Soc. Am. J. 70:555–569.

Schlesinger, W.H. 1999. Carbon and agriculture: Carbon sequestration in soils. Science 284:2095.

Tortoso, A.C., and G.L. Hutchinson. 1990. Contributions of autotrophic and heterotrophic nitrifiers to soil NO and N_2O emissions. Appl. Environ. Microbiol. 56:1799–1805.

Trinsoutrot, I., S. Recous, B. Mary, and B. Nicolardot. 2000. C and N fluxes of decomposing ^{13}C and ^{15}N *Brassica napus* L.: Effects of residue composition and N content. Soil Biol. Biochem. 32:1717–1730.

Venterea, R.T., M. Burger, and K.A. Spokas. 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. J. Environ. Qual. 34:1467–1477.

Wagai, R., K.R. Brye, S.T. Gower, J.M. Norman, and L.G. Bundy. 1998. Land use and environmental factors influencing soil surface CO_2 flux and microbial biomass in natural and damaged ecosystems in southern Wisconsin. Soil Biol. Biochem. 30:1501–1509.

Zeevi, M. 2008. Trial reports of The Israel Bio-Organic Agriculture Association (IBOAA). (In Hebrew.) Available at http://www.organic-israel.org.il (verified 2 Jan. 2010).