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

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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 CO₂ and N₂O. The objective of this study was to quantify the effects of management practices in irrigated sweet corn (Zea mays L.) on CO₂ and N₂O 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) CO₂ and N₂O fluxes in residue-amended plots and in NR plots. Carbon dioxide and N₂O fluxes were correlated with soil NH₄ concentrations and with days since tillage and days since seeding. Fluxes of CO₂ were correlated with soil water content, whereas N₂O fluxes had higher correlation with air temperature. Annual CO₂ emissions were higher with PCM than with CR and NR (9.7, 2.9, and 2.3 Mg C ha⁻¹, respectively). Fluxes of N₂O were 34.4, 0.94, and 0.77 kg N ha⁻¹ with PCM, CR, and NR, respectively. Annual amounts of CO₂-C and N₂O-N emissions from the PCM treatments were 64 and 3% of the applied C and N, respectively. Regardless of cultivation practices, elevated N₂O 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 CO₂ and N₂O are on the rise, with an average increase of 1.9 μL CO₂ L⁻¹ per year from 1995 to 2005 and an increase of N₂O 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 CO₂ and N₂O 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 CO₂ 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 N₂O. The rates of decomposition and release of N from OW in soils greatly depend 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 N₂O from soils (Tortoso and Hutchinson, 1990; Johnson et al., 2007). Nitrous oxide is an intermediate in
denitrification (reduction of \( \text{NO}_3^- \) to \( \text{N}_2 \)) and is also an intermediate product of nitrification (oxidation of \( \text{NH}_4^+ \) to \( \text{NO}_3^- \)). Temperature, soil moisture content, pH, and type and availability of nitrogen-containing substrates are the main factors affecting the emissions of \( \text{N}_2\text{O} \) (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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) (Buyanovsky and Wagner, 1983; Johnson et al., 2007). Two important controls on the rate of \( \text{CO}_2 \) loss from the soil surface are the rate of biological production of \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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 \( \text{N}_2\text{O} \) emissions (Ventera 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 \( \text{CO}_2 \) and \( \text{N}_2\text{O} \) 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 \( \text{CO}_2 \) and \( \text{N}_2\text{O} \) 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 \( \text{pH}_{\text{H}_2\text{O}} \) of 7.3; and \( \text{CaCO}_3 \) <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 \( \text{NH}_4^+ \), 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>
<thead>
<tr>
<th>Residue</th>
<th>Growing year</th>
<th>TC†</th>
<th>TN</th>
<th>Applied C</th>
<th>Applied N</th>
<th>Application date</th>
<th>Incorporation date</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>2006</td>
<td>444</td>
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<td>1838</td>
<td>70</td>
<td>30 Nov. 2005</td>
<td>5 Dec. 2005</td>
</tr>
<tr>
<td>PCM</td>
<td>2006</td>
<td>380</td>
<td>47.5</td>
<td>10640</td>
<td>1230</td>
<td>28 Nov. 2005</td>
<td>5 Dec. 2005</td>
</tr>
</tbody>
</table>

† TC, total C; TN, total N.
‡ CR, corn residues; PCM, pasteurized chicken manure.
Martinez, CA). 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$_2$O 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$_2$O 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:

$$\text{1 μL} \text{N}_2\text{O L}^{-1} = 341.2262/(273.15 + T_{air}) \text{ ng N cm}^{-3} \quad [1]$$

$$\text{1 μL CO}_2 \text{ L}^{-1} = 0.1462398/(273.15 + T_{air}) \text{ μg C cm}^{-3} \quad [2]$$

where $T_{air}$ 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):

$$\text{Daily average gas flux} = RQ^{\text{DAT}-7/10} \quad [3]$$

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$_2$O (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$_2$O 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.

#### 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.

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.

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...
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.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>df</th>
<th>( \theta ) %, volumetric</th>
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</thead>
<tbody>
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<td>Amendment</td>
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<td></td>
</tr>
<tr>
<td>PCM†</td>
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<td></td>
</tr>
<tr>
<td>CR</td>
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<td></td>
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<tr>
<td>NR</td>
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<tr>
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<tr>
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<tr>
<td>ST</td>
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<tr>
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<td>( F ) significance</td>
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</tbody>
</table>

† 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.

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\(_2\)O 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\(_2\)O 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 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\(_2\)O 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\(_2\)O; in the PCM NT plots, the flux of N\(_2\)O (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\(_2\)O emissions than the ST plot. In the CR treatments, the plots without corn plants had lower N\(_2\)O emissions than the ST plots with corn.

Similar to CO\(_2\), annual emission of N\(_2\)O 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\(_2\)O fluxes but not during the corn-growing season (Table 4).

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 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.
was substrate for the ammonium-oxidizing bacteria responsible for N₂O production through nitrification (Torstoso 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 NH₄ and NO₃), is very similar to a figure that presents NO₃ 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 NH₄ percentages were 40, 87, and 68% of total inorganic N in January 2006, January 2007, and January 2008, respectively. The high correlation of N₂O emissions with NH₄ rather than inorganic N indicates that the N₂O 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 NH₄ concentration in soil solution with CO₂ 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 CO₂ 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 CO₂ (Table 5). The high fluxes of CO₂ 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 N₂O flux, but the effect of time after seeding on flux of N₂O did not meet the 0.05 significance level of the stepwise analysis and was not reported. Time after tillage had a significant effect on CO₂ and N₂O fluxes (Tables 5 and 6). The highest peaks of CO₂ and N₂O 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

![Graph of CO₂ and N₂O fluxes over time](image-url)
allows the release of trapped CO₂ from the soil to the atmosphere as a result of the tillage. Tillage also reduces soil temperature; therefore, the rate of decomposition is lower.

In NT practice, the residues, which are spread over the surface, have less contact with soil particles and maintain a lower soil temperature. Consequently, CO₂ emissions after residue application are lower than obtained with CR and NR plots. Poultry litter applied on the surface application of PCM resulted in much higher fluxes of CO₂ and N₂O within the first 4 days after application. However, high CO₂ and N₂O fluxes were also observed in other studies. Significantly higher NO emissions occurred only if there was rainfall immediately after application of inorganic N fertilizer. Although the N₂O peaks occurred immediately after rainfall, the stepwise regression did not reveal a significant effect of water content on N₂O flux. Unlike N₂O, higher fluxes of CO₂ were correlated with high soil water content. Optimal water contents for biological activity existed in the upper 5-cm soil layer.

Carbon dioxide emissions from the soil surface were correlated with the CO₂ concentration gradients in the soil atmosphere according to the following relationship:

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

where \( Y \) is CO₂ flux (kg ha⁻¹ h⁻¹) and \( X \) is the gradient of CO₂ in the soil atmosphere (mL L⁻¹) between 50 and 10 cm.
Concentrations of CO₂ 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 CO₂ emission fluctuations. In the present work, CO₂ concentrations were measured in ST-without crop plots only, which received minimal irrigation in corn-growing season; therefore, the combined effects of CO₂ concentrations in soil atmosphere and soil moisture on CO₂ emissions could not be examined.

### Carbon Budget of Amended Plots

The calculated annual emission CO₂–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 CO₂ 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 CO₂–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 CO₂–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 CO₂–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.
Prolonged and continual PCM application will probably have an effect on SOM.

**Annual Emission of Nitrous Oxide**

The \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \), 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 \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \).

**Conclusions**

The data collected during this 3-yr field experiment showed that \( \text{CO}_2 \) and \( \text{N}_2\text{O} \) emissions from residue-amended soils were affected by climatic and management factors. The total annual amount of \( \text{CO}_2 \) 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 \( \text{N}_2\text{O} \) (mean, 34.4 kg N ha\(^{-1}\) yr\(^{-1}\)) were measured in the PCM treatment. These elevated \( \text{N}_2\text{O} \) emissions not only represent a loss of plant-available N, but, given the long atmospheric residence time and global warming potential of \( \text{N}_2\text{O} \) (296 times that of \( \text{CO}_2 \)), they are also important from a global climate point of view.
Carbon dioxide and N\textsubscript{2}O fluxes were well correlated with soil NH\textsubscript{4} concentration and with days since tillage and days since seeding. Carbon dioxide fluxes were correlated with soil water content, whereas N\textsubscript{2}O 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\textsubscript{2} fluxes but did not have a measureable effect on N\textsubscript{2}O 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.

Acknowledgments

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References


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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.

<table>
<thead>
<tr>
<th>Step</th>
<th>Parameter†</th>
<th>Coefficient</th>
<th>P value</th>
<th>R²</th>
</tr>
</thead>
<tbody>
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<td>44.74</td>
<td>&lt;0.0001</td>
<td>0.388</td>
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<td>2</td>
<td>T seed</td>
<td>17.14</td>
<td>&lt;0.0001</td>
<td>0.453</td>
</tr>
<tr>
<td>3</td>
<td>T tillage</td>
<td>5.90</td>
<td>0.0004</td>
<td>0.483</td>
</tr>
<tr>
<td>4</td>
<td>θ</td>
<td>5.89</td>
<td>0.1581</td>
<td>0.487</td>
</tr>
<tr>
<td>5</td>
<td>θ²</td>
<td>4.14</td>
<td>0.0532</td>
<td>0.496</td>
</tr>
</tbody>
</table>

† C sperm, NH4–N concentration in soil (mg kg⁻¹); T seed, 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.

<table>
<thead>
<tr>
<th>Step</th>
<th>Parameter†</th>
<th>Coefficient</th>
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<th>R²</th>
</tr>
</thead>
<tbody>
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<td>0.0383</td>
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<td>4</td>
<td>Temp max²</td>
<td>5.57</td>
<td>0.0170</td>
<td>0.473</td>
</tr>
</tbody>
</table>

† C sperm, NH4–N concentration in soil (mg kg⁻¹); T tillage, time after tillage (days); Temp max, air temperature (°C).