Greenhouse Gas Emissions from Nontilled, Permanent Raised, and Conventionally Tilled Beds in the Central Highlands of Mexico


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INTRODUCTION

Greenhouse gas emissions (GHGs) have been rising because of anthropogenic activity (Lokupitiya and Paustian, 2006), which causes changes in the radiative energy budget of Earth’s climate system (IPCC, 2007). This increase has affected Earth’s thermal equilibrium, inducing an increase in global temperature (Changsheng, 2007). Carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O) are the most important GHGs. Agricultural activities are an important source of anthropogenic GHGs, contributing to 20% of the annual atmospheric increase (Lemke et al., 2007).

In Mexico, 47% of the soil is considered degraded (SEMARNAT, 2002). Practices, such as deforestation, conventional crop production, intensive cattle raising, and changes in land use, have all contributed to soil degradation by altering soil physical, chemical, and biological characteristics, thereby reducing soil fertility. Conventional agricultural practices in the central highlands of Mexico consist of excessive soil tillage, removal of crop residues, and monoculture, leading to soil deterioration and loss of soil fertility (Sayre et al., 2001). Conservation agriculture in its version of permanent raised beds with crop rotation covers soil permanently through adequate residue retention, maintaining soil quality (Govaerts et al., 2005; Govaerts et al., 2007).

A rainfed field experiment was started in 1999 by the International Maize and Wheat Improvement Center (CIMMYT) at El Batán in the central highlands of Mexico to investigate the effect of tillage practices (permanent raised beds compared with conventionally tilled beds with residue retention) and residue management in permanent beds (PBs) (full and no residue retention) on crop yields and soil quality (Govaerts et al., 2007). Raised beds with no till can save up to 50% irrigation water depending on local conditions, crop, and soil type compared with tilled beds, whereas yields can increase by 8% and costs reduce by 25% because of decreased use of machinery (Aquino, 1998). Additionally, adequate crop residue retention increases organic matter and the C sequestered in soil (West and Marland, 2002). Less tillage improves soil structure, preventing soil degradation (Mrabet et al., 2001), and mitigates GHG emissions (Gregorich et al., 2005). Furthermore, reducing tillage decreases the use of machinery and thus GHG emissions (Robertson et al., 2000; Six et al., 2004).

The practice of permanent raised beds with adequate crop residue retention is actively promoted throughout the world for its obvious economical and environmental benefits, but little is known about how GHG emissions might be affected by this agricultural practice. A previous laboratory study showed that dynamics of C and N and GHG emissions were affected (Patiño-Zúñiga et al., 2009). Permanent raised bed planting with crop residue retention decreased the emissions of N$_2$O and CO$_2$ compared with soil under conventionally tilled raised beds. The study by Patiño-Zúñiga et al. (2009), however, was done in the laboratory, and it is well known that soil processes are affected by a wider range of factors in the field, for example, soil structure, crop, fluctuating temperature, and moisture content. Thus, GHG emissions might be affected in different ways in the field than in the laboratory.

Numerous studies have been published in which the effect of no-till versus conventional tillage on soil characteristics, such as soil water content and temperature; GHG emissions, that is, CO$_2$, CH$_4$, and N$_2$O; mineral N content, that is, ammonium (NH$_4^+$), nitrite (NO$_2^-$), and nitrate (NO$_3^-$); and soil organic carbon (SOC), has been investigated. The objective of this study was to investigate how permanent raised beds with removal or retention of crop residues and conventionally tilled beds with retention of crop residues affected soil water content and temperature; concentrations of mineral N (NH$_4^+$, NO$_2^-$, and NO$_3^-$); and fluxes of CO$_2$, CH$_4$, and N$_2$O for rainfed conditions in the central highlands of Mexico. Further, the global warming potential (GWP) of agricultural systems was determined considering additional contributors to GHG emissions, such as machinery and fertilizer use, and the amount of C sequestered in the 0–60 cm soil layer.
MATERIALS AND METHODS

Site Description

The research was conducted at the El Batán experimental station (19.318° N, 98.508° W; 2249 masl) situated in the semiarid, subtropical highlands of central Mexico. The growing period at El Batán has an average length of 132 days (FAO, 1978). The station has a mean annual temperature of 14°C (calculated across 1990–2001) and an average annual rainfall of 600 mm/year, with about 520 mm falling between May and October (Patiño-Zúñiga et al., 2009). Short, intense rain showers followed by dry spells typify the rainy season, and evapotranspiration exceeds rainfall throughout the year, as the total amount of yearly potential evapotranspiration is 1900 mm.

The soil at El Batán is classified as a haplic phaeozem (clayic) in the World Reference Base system (IUSS Working Group WRB 2007) and as a fine, mixed, thermic cumulic haplustoll in the United States Department of Agriculture Soil Taxonomy system (Soil Survey Staff, 2003; Govaerts et al., 2007). The particle size distribution was clay 409 g/kg, silt 240 g/kg, and sand 351 g/kg (Govaerts et al., 2005). Further details of the soil characteristics can be found in the work of Patiño-Zúñiga et al. (2009).

Field Experiment

A long-term rainfed experiment was started in 1999, which consisted of individual plots of 6 × 20 m with 8 beds of 75 cm width from furrow to furrow. The experiment included duplicate plots arranged in a randomized complete-block design with 14 different treatments, but only three treatments were used in this research. Two management factors were investigated in the field trial. The first one was tillage practices whereby conventional tilled beds (CBs), tilled and formed after each crop, were compared with PBs with continued reuse of existing beds (reshaped before each crop). The second factor studied the effect of residue management where, for the PB system, all crop residues were chopped and retained on the field or all residues were removed for fodder. In the CBs, all residues were incorporated into the soil through tillage. The tillage operations after harvest in a CB consisted of one pass with a chisel plow to 30 cm depth, followed by two passes with a disk harrow to 20 cm depth and two passes with a spring-tooth harrow to 10 cm. The spring-tooth harrow was used when needed for weed control (typically twice) during the dry season. To prepare the seedbed in May, the tillage operations of December were repeated (with one pass with the spring-tooth harrow), after which beds were made. The PB plots were reshaped after harvest. Weed control during the dry season was achieved with glyphosate. Wheat (Triticum aestivum L.) and maize (Zea mays L.) were planted in a yearly rotation. During this research, wheat was cultivated on all plots included in the study.

Standard practices in the study included the use of currently recommended crop cultivars, with maize planted at 60,000 plants/ha in one row on top of the 75 cm beds and two rows of wheat planted in 20 cm rows on top of the beds at 110 kg seed/ha. Both crops were fertilized at the rate of 150 kg N/ha using urea with all N banded on top of the bed before wheat was planted and at planting for maize. Weed control used appropriate, available herbicides as needed, and no disease or insect pest controls were applied, except for seed treatments applied by commercial seed sources. In 2008, the CB plots were tilled on May 5, and beds were made on May 6. The PB plots were reshaped on May 9. The wheat plots were fertilized on May 13, and wheat was planted on May 26. Tillage after harvest in CBs was done on December 17 to prepare the seedbed for the next cycle on May 15, 2009. The beds in the CB plots were made and the beds in the PB plots reshaped on the same day, and maize was planted on May 27, 2009.
Measurement of Greenhouse Gas Emissions

The monitoring of fluxes of GHGs started on June 20, 2008, and ended on June 22, 2009. The emissions of CO$_2$, CH$_4$, and N$_2$O were measured simultaneously. Four chambers were placed per plot and used to determine the fluxes. The chambers had a length of 25 cm and an inner diameter of 20 cm and were designed as suggested by Parkin et al. (2003) with a coated top and a sampling port with a butyl rubber stopper. The chambers were inserted 5 cm into the soil so that the height from the soil surface to the top of a chamber was 20 cm. At sowing, the chambers were removed, and they were reinserted into the soil in the same place after sowing. At harvest and tillage, this procedure was repeated. Gas sampling was done between 9:00 and 11:00 AM. At sampling, covers were placed on the chambers and sealed airtight with Teflon tape. At 0, 20, 40, and 60 minutes after the chamber was sealed, 15 cm$^3$ of air was injected into the polyvinyl-chloride (PVC) chamber headspace, while the gas was mixed by flushing at least three times with the air inside the chamber, followed by gas collection for analysis. The 15 cm$^3$ air sample was injected into 15 cm$^3$ evacuated vials closed with a butyl rubber stopper and sealed with an aluminum cap, pending analysis.

The headspace of the vials was analyzed for CO$_2$ and N$_2$O on an Agilent Technologies, Santa Clara, California, 4890D gas chromatograph fitted with an electron capture detector. An HP-PLOT Q 30 m column with the temperature of the detector, injector, and oven at 225°C, 100°C, and 35°C, respectively, was used to separate CO$_2$ and N$_2$O from the other gases. The flow rate of the carrier gas N$_2$ was 6 mL/min. The CH$_4$ in the vials was analyzed on an Agilent Technologies 4890D gas chromatograph fitted with a flame ionization detector. A PORAPAK Q 80/100 12' × 1/8" × 0.085" column with the detector at 310°C, injector at 100°C, and oven at 32°C was used to separate CH$_4$ from the other gases. The flow rate of the carrier gas He was 25 mL/min.

Concentrations of CO$_2$, N$_2$O, and CH$_4$ were calculated by comparing peak areas against a standard curve prepared from known concentrations, that is, 10 ppm N$_2$O in N$_2$; 5 ppm CH$_4$ in N$_2$; and 2,500, 20,000, and 40,000 ppm CO$_2$ in N$_2$, every time samples were analyzed.

Soil Sampling and Analysis

Soil was sampled for mineral N, that is, NH$_4^+$, NO$_2^-$, and NO$_3^-$, and water content when GHG emissions were determined. Four soil cores were taken from the 0–20 cm soil layer of the beds at random. Two samples were taken from the opposite corners of a plot and pooled to give two composite samples. Two subsamples of 20 g soil from each of the two samples taken for the four treatments were added to 250 mL bottles and extracted for NH$_4^+$, NO$_2^-$, and NO$_3^-$ with 100-mL 0.5-M K$_2$SO$_4$ filtered through Whatman$^\text{®}$ filter paper no. 42 and stored at −20°C, pending analysis. The rest of the samples were weighed and dried for 24 hours at 105°C. Oven-dry weight was then determined and gravimmetrical moisture content calculated. Soil temperature was determined at a depth of 10 cm.

After harvest, samples were taken from the 0–20, 20–40, and 40–60 cm layers from four places in each plot to determine total C and bulk density. A core sample with a diameter of 5 cm was used. For each depth, a core sample with a height of 5 cm was weighed and oven-dried at 105°C to determine soil water content and bulk density. Soil bulk density was computed as oven-dry mass to volume ratio using the core method (Grossman and Reinsch, 2002). The remainder of the soil was used for the determination of total C.

Total C was measured with a Shimadzu total organic carbon analyzer (Japan), whereas total N was measured by the Kjeldahl method using concentrated H$_2$SO$_4$, K$_2$SO$_4$, and CuSO$_4$ to digest the samples (Bremner, 1996). The NH$_4^+$, NO$_2^-$, and NO$_3^-$ in the K$_2$SO$_4$ extracts were determined colorimetrically on a SKALAR® San Plus System automatic analyzer (Mulvaney, 1996).
Statistical Analysis

Emissions of CO₂, CH₄, and N₂O were regressed on elapsed time, that is, 0, 20, 40, and 60 minutes, using a linear model forced to pass through the origin but allowing different slopes (production rates). The sample at time 0 accounted for atmospheric CO₂, CH₄, and N₂O and was subtracted from the measured values.

Soil characteristics, that is, bulk density; water content and temperature; C content in the 0–20, 20–40, 40–60, and 0–60 cm layers; and concentrations of NH₄⁺, NO₂⁻, and NO₃⁻, were subjected to one-way analysis of variance using PROC GLM (SAS Institute, 1989) to test for significant differences among treatments. Significant differences between treatments for CO₂, CH₄, and N₂O emission rates were determined using PROC MIXED, considering repeated measurements (SAS Institute, 1989).

The total emissions of CO₂, N₂O, and CH₄ during the experimental period, that is, June 20, 2008, to June 22, 2009, were calculated by the linear interpolation of data points between each successive sampling event (Ussiri et al., 2009) and the numerical integration of underlying area using the trapezoid rule (Whittaker and Robinson, 1967).

Calculation of Net Global Warming Potential

The calculation of net GWP was based on the work of Robertson, Paul, and Harwood (2000) and Thelen et al. (2010), taking into account soil C sequestration (Δ soil C GWP), emissions of GHGs from soil (soil N₂O flux + soil CH₄ flux), emissions of GHGs from fuel used for farm operations (glyphosate application, tillage, planting and fertilizer application, harvest) (operation GHG flux), and the production of fertilizer and seeds (input GHG flux). Net GWP was calculated as follows:

\[
\text{Net GWP} = \Delta \text{soil CGWP} + \text{soil N}_2\text{O flux} + \text{soil CH}_4 \text{ flux} + \text{operation GHG flux} + \text{input GHG flux}
\]

Changes in carbon stock per year since the beginning of the experiment (10 years) were calculated with SOC in CB with crop residue retained as reference. The values used for agronomic inputs were obtained from the work of West and Marland (2002). The same values were used for chisel and disk plowing. The C emission for a spring-tooth harrow pass and the reshaping of PB were counted as half of a disk plow pass. The making of CB was counted as a disk plow pass. Additionally, the CO₂ emitted when urea is hydrolyzed in the field was not considered (Snyder et al., 2009). The GWP of the gasses emitted was calculated considering the CO₂-equivalent emissions of 298 for N₂O, 25 for CH₄, and 1 for CO₂ (IPCC, 2007).

RESULTS

Soil Characteristics

The average air temperature during the experimental period was 25.3°C. The average soil temperature was 19.7°C in a CB and significantly (2.7°C) lower in a PB with residue retention (P < .0001) (Figure 15.1a; Table 15.1). Removing the crop residue from a PB increased the average soil temperature significantly (3.4°C) (P < .0001).

The soil water content fluctuated markedly during the rainy season, that is, from June to October, because of the erratic rainfall in the region (Figure 15.1b). The soil water content was significantly higher in PB than in CB with residue retention (P = .0263); the removal of crop residues
in PB significantly reduced the water content in soil compared with soil where they were retained ($P < .001$) (Table 15.1).

The total C in the 0–20 cm soil layer was significantly higher in the PB than in the CB with residues retained in both systems ($P = .0047$) but not in the other soil layers (Table 15.2). The apparent density of the different soil layers was not affected by tillage.

Total C was significantly higher in the 0–20 cm and 40–60 cm soil layers of the PB with residue retained than where residue was removed, but not in the 20–40 cm layer ($P \leq .0280$). The apparent soil density was not affected by crop residue management. The total C in the 0–60 cm soil layer was not affected by tillage, but removal of residue significantly reduced it in PBs compared with PBs where residue was retained ($P < .0036$) (Table 15.3).

**Concentrations of NH$_4^+$, NO$_2^-$, and NO$_3^-$**

The concentration of NH$_4^+$ was high in soil, that is, >100 mg NH$_4^+$-N/kg, just after the application of urea, but it was rarely >25 mg NH$_4^+$-N/kg thereafter (Figure 15.2a). The concentration of
Table 15.1  Effect of Residue Management and Tillage on Soil Temperature (°C) and Volumetric Water Content (WC) (g/dm$^3$); Concentrations of NH$_4^+$, NO$_2^−$, and NO$_3^−$ (mg N/kg); and Emissions of CO$_2$(kg C/ha/day), CH$_4$ (g C/ha/day), and N$_2$O (g N/ha/day)$^a$  

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Temperature(°C)</th>
<th>WC(g/dm$^3$)</th>
<th>NH$_4^+$</th>
<th>NO$_2^−$ (mg N/kg)</th>
<th>NO$_3^−$</th>
<th>N$_2$O(g N/ha/day)</th>
<th>CH$_4$(g C/ha/day)</th>
<th>CO$_2$(kg C/ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilled beds (CB)</td>
<td>19.7 a</td>
<td>234 b</td>
<td>12.7 a</td>
<td>1.54 a</td>
<td>26.6 a</td>
<td>8.63 a</td>
<td>0.481 a</td>
<td>9.15 a</td>
</tr>
<tr>
<td>Nontilled beds (PB)</td>
<td>17.0 b</td>
<td>253 a</td>
<td>11.1 b</td>
<td>0.77 b</td>
<td>10.0 b</td>
<td>6.13 b</td>
<td>-0.362 b</td>
<td>8.91 a</td>
</tr>
<tr>
<td>MSD$^b$</td>
<td>0.3</td>
<td>17</td>
<td>4.8</td>
<td>0.37</td>
<td>4.4</td>
<td>0.34</td>
<td>0.151</td>
<td>0.18</td>
</tr>
<tr>
<td>$P$ value</td>
<td>&lt;.0001</td>
<td>.0263</td>
<td>.5052</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>.0130</td>
<td>.0312</td>
<td>.7629</td>
</tr>
<tr>
<td>$F$ value</td>
<td>258.54</td>
<td>5.00</td>
<td>0.44</td>
<td>16.67</td>
<td>54.99</td>
<td>28.24</td>
<td>14.74</td>
<td>.11</td>
</tr>
</tbody>
</table>

Effect of tillage when all crop residues was retained

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Temperature(°C)</th>
<th>WC(g/dm$^3$)</th>
<th>NH$_4^+$</th>
<th>NO$_2^−$ (mg N/kg)</th>
<th>NO$_3^−$</th>
<th>N$_2$O(g N/ha/day)</th>
<th>CH$_4$(g C/ha/day)</th>
<th>CO$_2$(kg C/ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residue removed</td>
<td>20.1 a</td>
<td>212 b</td>
<td>11.8 a</td>
<td>1.34 a</td>
<td>20.4 a</td>
<td>5.98 a</td>
<td>-0.257 a</td>
<td>7.61 b</td>
</tr>
<tr>
<td>Residue retained</td>
<td>17.0 b</td>
<td>253 a</td>
<td>11.1 a</td>
<td>0.77 b</td>
<td>10.0 b</td>
<td>6.13 b</td>
<td>-0.362 a</td>
<td>8.91 a</td>
</tr>
<tr>
<td>MSD$^b$</td>
<td>0.3</td>
<td>15</td>
<td>5.0</td>
<td>0.26</td>
<td>5.0</td>
<td>0.32</td>
<td>0.205</td>
<td>0.24</td>
</tr>
<tr>
<td>$P$ value</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>.7883</td>
<td>&lt;.0001</td>
<td>&lt;.0001</td>
<td>.7506</td>
<td>.7409</td>
<td>.0318</td>
</tr>
<tr>
<td>$F$ value</td>
<td>342.41</td>
<td>28.94</td>
<td>0.07</td>
<td>18.31</td>
<td>16.80</td>
<td>0.12</td>
<td>0.13</td>
<td>14.50</td>
</tr>
</tbody>
</table>

| Effect of crop residue management in PBs |

$a$ Treatments with the same letter are not significantly different from each other, that is, within the column.

$^b$ MSD: minimum significant difference ($P < .05$).

$^c$ SEE: standard error of the estimate ($P < .05$).
### Table 15.2  Effect of Crop Residue Management and Tillage on Total C (g/kg), Apparent Density (kg/dm³), and Volumetric Water Content (g/dm³)

<table>
<thead>
<tr>
<th>Soil Layer</th>
<th>Treatment</th>
<th>0–20 cm</th>
<th>20–40 cm</th>
<th>40–60 cm</th>
<th>MSDa</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total C (g/kg soil)</strong></td>
<td>Tilled beds (CB)</td>
<td>10.7 B² a²</td>
<td>9.9 A a</td>
<td>9.5 A a</td>
<td>3.1</td>
<td>0.63</td>
<td>.5535</td>
</tr>
<tr>
<td></td>
<td>Nontilled beds (PB)</td>
<td>13.6 A a</td>
<td>8.9 A b</td>
<td>9.3 A b</td>
<td>2.4</td>
<td>17.60</td>
<td>.0008</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>2.0</td>
<td>3.2</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F value</td>
<td>12.47</td>
<td>0.57</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P value</td>
<td>.0123</td>
<td>.4781</td>
<td>.7950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Apparent density (kg/dm³)</strong></td>
<td>Tilled beds (CB)</td>
<td>1.13 A b</td>
<td>1.43 A a</td>
<td>1.39 A a</td>
<td>0.12</td>
<td>29.31</td>
<td>.0001</td>
</tr>
<tr>
<td></td>
<td>Nontilled beds (PB)</td>
<td>1.27 A a</td>
<td>1.34 A a</td>
<td>1.36 A a</td>
<td>0.19</td>
<td>0.93</td>
<td>.4278</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>0.14</td>
<td>0.10</td>
<td>0.16</td>
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</tr>
<tr>
<td></td>
<td>F value</td>
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<td>4.94</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P value</td>
<td>.0612</td>
<td>.0679</td>
<td>.6134</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Volumetric water content (g/dm³ soil)</strong></td>
<td>Tilled beds (CB)</td>
<td>218 A b</td>
<td>325 A a</td>
<td>316 A a</td>
<td>64</td>
<td>13.45</td>
<td>.0020</td>
</tr>
<tr>
<td></td>
<td>Nontilled beds (PB)</td>
<td>279 A a</td>
<td>324 A a</td>
<td>341 A a</td>
<td>77</td>
<td>2.68</td>
<td>.1219</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>78</td>
<td>46</td>
<td>58</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>F value</td>
<td>3.68</td>
<td>0.00</td>
<td>1.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P value</td>
<td>.1034</td>
<td>.9576</td>
<td>.3303</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total C (g/kg soil)</strong></td>
<td>Residue removed</td>
<td>10.2 B a</td>
<td>7.4 A b</td>
<td>7.0 B b</td>
<td>2.6</td>
<td>7.13</td>
<td>.0139</td>
</tr>
<tr>
<td></td>
<td>Residue retained</td>
<td>13.6 A a</td>
<td>8.9 A b</td>
<td>9.3 A b</td>
<td>2.4</td>
<td>17.60</td>
<td>.0008</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>1.9</td>
<td>2.7</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F value</td>
<td>19.16</td>
<td>2.01</td>
<td>8.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P value</td>
<td>.0047</td>
<td>.2061</td>
<td>.0280</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Apparent density (kg/dm³)</strong></td>
<td>Residue removed</td>
<td>1.25 A a</td>
<td>1.41 A a</td>
<td>1.23 A a</td>
<td>0.21</td>
<td>3.79</td>
<td>.0639</td>
</tr>
<tr>
<td></td>
<td>Residue retained</td>
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<td>1.34 A a</td>
<td>1.36 A a</td>
<td>0.19</td>
<td>0.93</td>
<td>.4278</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
<td>0.19</td>
<td>0.11</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F value</td>
<td>0.07</td>
<td>2.73</td>
<td>2.37</td>
<td></td>
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<tr>
<td></td>
<td>P value</td>
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<td>.1494</td>
<td>.1747</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Volumetric water content (g/dm³ soil)</strong></td>
<td>Residue removed</td>
<td>216 A a</td>
<td>241 B a</td>
<td>189 B a</td>
<td>63</td>
<td>2.66</td>
<td>.1236</td>
</tr>
<tr>
<td></td>
<td>Residue retained</td>
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<td>324 A a</td>
<td>341 A a</td>
<td>77</td>
<td>2.68</td>
<td>.1219</td>
</tr>
<tr>
<td></td>
<td>MSD</td>
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<td>54</td>
<td>46</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>F value</td>
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<td>14.20</td>
<td>67.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P value</td>
<td>.1008</td>
<td>.0093</td>
<td>.0002</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

a MSD: minimum significant difference (P < .05).

b Values with the same capital letter are not significantly different between the treatments, that is, columns (P < .05).

c Values with the same letter are not significantly different between the layers, that is, rows (P < .05).
NH$_4^+$ was not significantly affected by tillage, that is, comparing CBs with PBs and crop residue
retention, or crop residue management, that is, removal or retention of crop residues (Table 15.1).

The concentration of NO$_3^-$ fluctuated across the growing season but tended to increase toward
the end of the season, that is, when soil became drier because of less precipitation (Figure 15.2b).
The concentration of NO$_3^-$ was significantly higher in CBs than in PBs with crop residue retention
in both treatments ($P < .0001$) (Table 15.1). The concentration of NO$_3^-$ was significantly higher in
soil with PBs where the residue was removed compared with soil where the residue was retained
($P < .0001$).

The concentration of NO$_2$ was high, that is, $>50$ mg N/kg, after the application of urea, but it
generally remained $<50$ mg N/kg thereafter (Figure 15.2c). The concentration of NO$_3^-$ was significantly higher in CBs than in PBs with crop residue retention in both treatments ($P < .0001$) (Table 15.1). The concentration of NO$_2$ was significantly higher in soil with PBs where the residue was removed compared with soil where the residue was retained ($P < .0001$).

The concentration of NO$_3^-$ was significantly lower in soil when crop residue was retained compared with when it was removed ($P < .0001$) (Table 15.1).

**Fluxes of CO$_2$, CH$_4$, and N$_2$O**

The emission of CO$_2$ was $<11$ kg CO$_2$-C/ha/day in May and June, increased in July and
August to approximately 35 kg CO$_2$-C/ha/day, and remained $<11$ kg CO$_2$-C/ha/day thereafter (Figure 15.3a). The emission of CO$_2$ was not significantly affected by tillage (Table 15.1). Removing the crop residue from PBs significantly reduced the emission of CO$_2$ 1.2 times compared with soil where the residue was retained ($P = 0.0318$).

The emission of CH$_4$ was highly variable across time and ranged from $-10.9$ g CH$_4$-C/ha/day in soil in CBs where the residue was retained at day 215 (December) to a maximum of 11.8 g CH$_4$-C/ha/day in PBs with residue retention at day 71 (July) (Figure 15.3b). The emission of CH$_4$ was negative in the PB treatment, that is, CH$_4$ was oxidized, and positive in the CB treatment, that is, CH$_4$ was produced and significantly larger in the latter ($P = 0.0312$) (Table 15.1). Crop residue management had no significant effect on the emission of CH$_4$.
The emission of N₂O was <5 g N₂O-N/ha/day in May, increased in June and the beginning of July to >89 g N₂O-N/ha/day, and remained <5 g N₂O-N/ha/day thereafter (Figure 15.3c). The emission of N₂O was significantly affected by tillage ($P = .0130$), but the removal of crop residue in PBs had no significant effect on N₂O emission (Table 15.1).
Figure 15.3 Emissions of (a) carbon dioxide (CO$_2$), (b) methane (CH$_4$) (mg C/kg dry soil), and (c) nitrous oxide (N$_2$O) (mg N/kg dry soil) in soil at El Batán from May 2008 until March 2009 with conventionally tilled beds and crop residue retention (CB) (○) and with permanent raised beds (PB) and crop residue removed (□) or retained (■).
Global Warming Potential

The total diesel use was different between PB and CB but not within the different treatments of PB. The use of machinery to remove crop residue was not considered in the calculation, so the difference in equivalent CO₂ emission between the treatments depended only on tillage, that is, 118 kg CO₂/ha/year in CBs and 45 kg CO₂/ha/year in PBs.

Fertilizer production and seed production were the same for each of the treatments, so their contribution to GWP was similar, that is, 143 kg CO₂/ha/year (Table 15.4). The contribution of GHGs to GWP was lowest in the PB with crop residues retained, that is, 527 kg CO₂/ha/year, and highest in the PB with crop residue removal, that is, 801 kg CO₂/ha/year. The amount of C in the 0–60 cm soil layer was lowest in the PB with removal of crop residues, that is, 63.1 Mg C/ha, and highest in the PB with crop residues retained, that is, 83.4 Mg C/ha. The net GWP was lower in the CB with crop residue retention, that is, 1062 kg CO₂/ha/year, than in the PB with crop residue removal, that is, −681 kg CO₂/ha/year.

DISCUSSION

Soil Characteristics

Soil temperature was higher in CBs where residue was incorporated through tillage than in PBs with residue retention on the surface. The importance of retaining crop residues to soil temperatures can also be seen in the PB systems with different residue management. Soil temperature was significantly higher in the PB where the crop residue was removed than where it was retained. Different processes affect soil temperature. Residue left on the soil surface reflects solar radiation and insulates the soil surface (Shinners et al., 1993). Because soil particles have lower heat capacity
and greater heat conductivity than water, dry soils potentially warm up and cool down faster than wet soils (Hillel, 1998). Tillage accelerates soil drying and heating/cooling as it disturbs the soil surface, thereby further increasing differences in soil temperature. Tillage also increases air pockets in which evaporation occurs, further accelerating soil drying and heating (Licht and Al-Kaisi, 2005). Ussiri and Lal (2009) reported that tillage significantly affected soil temperature in the 0–5 cm layer of an arable soil in Ohio. During summer and early autumn, temperatures were reported to be significantly higher under chisel (25.9°C) and moldboard plow till (26.5°C) than under no-till (23.1°C) (Ussiri and Lal, 2009), as found in our study. They found opposite results in late autumn and winter as crop residues in the no-till system protected the soil against freezing.

Wheat is traditionally planted in the central highlands of Mexico around mid-June, coinciding with the beginning of the rainy season that ends toward the end of October. Rainfall in the central highlands is erratic, which explains why the water content fluctuates so much across the growing season, with the water content sometimes decreasing to values found in the dry season, for example, toward the end of July (Figure 15.1b).

Tillage had a significant effect on soil water content (Table 15.1). Ussiri et al. (2009) reported that in no-till systems the surface soil moisture content was generally higher than in treatments with chisel and moldboard plow till during summer, spring, and autumn but not during winter and early spring. The structure of soil with PBs is better than that where beds were remade each year. This means what little precipitation falls in the dry season infiltrates the soil more rapidly with less runoff and evaporation (Shaver et al., 2002). This suggests that in drier years water shortage for growing crops will manifest itself earlier in CBs than in PBs if crop residues are retained (Borrell and Van Cooten, 1999).

The water content was significantly lower in PBs when residue was removed from soil compared with where it was retained (Table 15.1). Retaining crop residue on soil affects soil water content in different ways. A direct effect of retaining crop residue on the soil surface is that it forms a barrier against evaporation and prevents runoff (Ussiri and Lal, 2009). Additionally, crop residue retention improves soil structure, water-holding capacity, and soil stability, thereby facilitating water infiltration, and prevents soil drying (Lichter et al., 2008; Zibilske and Bradford, 2007). Crop residue retention also lowers soil temperature, which further reduces evaporation.

Total soil C was 1.3 times higher in the 0–20 cm layer under nontilled PBs than under tilled beds both with residues retained (Table 15.3). Ussiri and Lal (2009) found even larger increases as they reported that no-till increased the total SOC pool in the 0–15 cm layer 2.7 times compared with chisel till and 2.9 times compared with moldboard plow till. It is well documented that organic matter increases in nontilled soil in the 0–5 cm soil layer, compared with conventionally tilled soil (Sainju et al., 2006). No-till favors the formation of stable aggregates and physically protects organic matter, and thereby reduces mineralization rates (Lichter et al., 2008). Tillage and conventional plowing breaks up soil aggregates so that organic matter becomes available for decomposition (Bronick and Lal, 2004).

Tillage might reduce C in the topsoil layers but might increase it in the deeper soil layers as organic material is moved downward and mixed in the plow layer (VandenBygaart and Angers, 2006). In the experiment reported here, the C in the deeper soil layer was not significantly different between PBs and CBs. The total C in the 0–60 cm layer was 83.4 Mg C/ha in PBs and 79.2 Mg C ha in CBs with residue retention (Table 15.3). Ussiri and Lal (2009) reported values of 60.3 Mg C/ha in the 0–15 cm layer and 19.7 Mg C/ha in the 15–30 cm layer, that is, a total of 79.9 Mg C/ha in the 0–30 cm layer, after 43 years of no-till practice. For chisel till they reported values of 44.8 Mg C/ha and for moldboard till values of 45.3 Mg C/ha.

Removal of crop residues in PBs decreased the total C in each of the studied layers compared with retention of crop residues. In the experiment reported here, total C in the 0–60 cm soil layer was more than 24% lower when crop residue was removed compared with the soil where it was retained. Crop residue retention can have an important effect on soil organic matter content (Govaerts et al.,...
Albaladejo et al. (1998) reported that in soil under conventional agricultural practices and with removal of crop residues, the organic carbon content can decrease by 26% within a couple of years, whereas Dabney et al. (2004) reported a decrease of organic carbon content by 47% within 5 years. The soil bulk density of the three soil layers, that is, 0–20 cm, 20–40 cm, and 40–60 cm, was not affected by tillage after 10 years. Ussiri et al. (2009), however, reported that the bulk density was significantly lower in the 0–15 cm layer of continuous no-till than in the moldboard and chisel till after 43 years but not in the 15–30 cm layer. This can be caused by changes in micro- and macropore structures, as the soil was not disturbed (Ussiri et al., 2009); higher SOC content (Ussiri and Lal, 2009); and macrofauna activity (Dick et al., 1991). This difference in bulk density between no-till and conventional till was not observed in our study.

**Mineral Nitrogen in Soil**

Just after urea application, the concentration of NH$_4^+$ was >100 mg N/kg soil. Hydrolysis of urea generates two NH$_3$ molecules, sharply increasing the concentration of NH$_4^+$ in the soil (Burton and Prosser, 2001). The concentration of NH$_4^+$, however, dropped rapidly. Some NH$_3$ might have been lost through volatilization, but emission of NH$_3$ is only significant in alkaline soils (Willem, Sutton, and Schjørring, 1998). As such, most of the NH$_4^+$ was oxidized to NO$_3^-$, as evidenced by the large amounts of NO$_3^-$. Some increase in the concentration of NO$_2^-$ occurred between December and March. Gelfand and Yakir (2008) reported that in semiarid environments, upon rewetting nitrification occurs as a partially uncoupled two-step process, that is, oxidation of NH$_4^+$ to NO$_2^-$ and NO$_2^-$ to NO$_3^-$, thereby increasing the concentration of NO$_3^-$ in soil, as opposed to a rapid continuous oxidation in wetter conditions. The concentration of NO$_3^-$ dropped rapidly. Different processes contributed to this decrease, for example, plant uptake, denitrification, NO$_3^-$ leaching, and microbial N immobilization, especially when crop residue is retained with a high C:N ratio.

The concentration of mineral N, that is, sum of NH$_4^+$, NO$_2^-$, and NO$_3^-$, was higher in CBs than in PBs. Ussiri et al. (2009) reported opposite results and attributed them to less residue–soil interaction in no-till compared with moldboard or chisel till. This would lead to lower decomposition rates in no-till and less immobilization of N. The decrease in mineral N in our study, however, might be explained in the following way: in CBs crop residue was incorporated in the soil after harvest, whereas in PBs it remained on the soil surface. Immediately, soil microorganisms were in direct contact with the crop residue in CBs, favoring its decomposition. Additionally, tillage increases the availability of soil organic matter by soil aggregate disruption, enhancing C and N mineralization (Verachtert et al., 2009). In a PB, the incorporation of crop residues in soil is much slower and will be mostly attributed to macrofauna (e.g., earthworms) activity, which is often inhibited in dry conditions (Dangerfield, 1997). The crop was sown when the rainy season started. In a PB, incorporation and decomposition of the crop residue started and N was immobilized. Maize and wheat crop residues are characterized by a high C:N ratio; so when decomposition started, mineral N was immobilized (Verachtert et al., 2009). However, in a CB most of the organic material was already mineralized, so less N was immobilized. Consequently, as the mineralization of crop residue started later in the PB than in the CB, immobilization of N when crops were fertilized was larger in the PB than in the CB. As such, the inorganic N content in soil was higher in the CB than in the PB. The effect of crop residue on soil N content can also be seen in the crop residue management in the PB. Removing crop residues reduced N immobilization so that the mineral N content increased.

**Fluxes of Carbon Dioxide**

The maximum emission of CO$_2$, that is, approximately 3.5 g C/m$^2$/day, was found in PBs with residue retention and was similar to values reported by Duiker and Lal (2000) and Jacinthe et al. (2002). The daily emission of CO$_2$ was larger in July and August than in the rest of the year (Figure 15.3a).
This is presumably a combination of different factors. First, in the central highlands of Mexico, the rainy season starts at the end of June and soil water content increases as does microbial activity, hence the emission of CO₂. Second, the soil is fertilized with urea, which might stimulate the decomposition of organic material (Ussiri and Lal, 2009). As mentioned earlier, the C:N ratio of maize or wheat crop residue is high, so application of inorganic N will stimulate organic matter decomposition. Third, the crop starts growing and root exudates will provide C substrate for soil microorganisms, increasing their activity. It has often been reported that temperature is the factor that is best correlated with emissions of CO₂ (Almaraz et al., 2009b), but not in this experiment. In the semiarid highlands of Mexico, soil moisture content was significantly correlated with emissions of CO₂ (P < .0001), but temperature was not (Table 15.5).

The emission of CO₂ was not affected by tillage (Table 15.1). Different results have been reported for the effect of tillage on fluxes of CO₂. Emission of CO₂ is often lower in no-till than in conventional till (Almaraz et al., 2009b), although an increase in fluxes of CO₂ no-till has been reported compared with conventional tillage (Oorts et al., 2007). Carbon mineralization depends on the amount and characteristics of available organic C (Vanhala et al., 2007); management practices; soil conditions, that is, water content and temperature; and soil characteristics, such as pH (Saggar et al., 1999), cation exchange capacity, soil structure (Amato and Ladd, 1992), sodicity (Nelson et al., 1996), clay content (van Veen et al., 1985), and specific surface area of the clay and nature of the clay mineral (D’Acquili et al., 1998). Although some soil conditions, such as temperature, and soil characteristics, for example, electrolytic conductivity and organic matter in the 0–20 cm layer, were different between CBs and PBs, they do not appear to have affected the emission of CO₂. The

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Crop residues</th>
<th>Emission of CO₂</th>
<th>Emission of N₂O</th>
<th>Emission of CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBs</td>
<td>Retained</td>
<td>0.2858</td>
<td>0.0265</td>
<td>0.9534</td>
</tr>
<tr>
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<td>0.0856</td>
<td>0.3350</td>
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<td>0.0836</td>
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</tr>
<tr>
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<td>&lt;0.0001</td>
<td>0.2704</td>
</tr>
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</table>

*Values between parentheses are Prob < r under Ho: Rho = 0 (CORR Procedure, SAS Institute, 2009).*
emission of CO$_2$ was affected significantly by crop residue management in PBs. Removal of crop residue reduced C substrate for soil microorganisms so that their activity was reduced, that is, the emission of CO$_2$ decreased.

**Fluxes of Nitrous Oxide**

The fluxes of N$_2$O generally were $<5$ g N/ha/day, except in June and July when they often were $>20$ g N/ha/day. The high N$_2$O fluxes in June and July corresponded with the application of urea, that is, high NH$_4^+$ concentrations, high soil water contents, and large amounts of NO$_3^-$ in the soil profile. The emission of N$_2$O was significantly correlated with concentrations of NO$_3^-$ and with NH$_4^+$, except in CBs ($P < .0001$) (Table 15.5). It is well known that concentrations of NH$_4^+$ and NO$_3^-$ affect emissions of N$_2$O (Abdalla et al., 2010). Different processes and factors control N$_2$O emission from soil, but nitrification and denitrification are normally the most important processes (Menendez et al., 2008). They are controlled by environmental factors, cropping systems, soil management practices (Ellert and Janzen, 2008), inorganic or organic fertilization (Baggs et al., 2003), and water regimes (Zou et al., 2007). Denitrification is usually the main source of N$_2$O under conditions of high soil water content (Azam et al., 2002), which is not often found in our soil from the semi-arid highlands of Mexico. As such, it can be assumed that nitrification was the process that most contributed to N$_2$O production as the emission of N$_2$O was strongly correlated with the concentration of NH$_4^+$ in soil (Harrison and Webb, 2001). The use of N inorganic fertilizer in agriculture, such as urea, is often the main source of N$_2$O emissions from soil (Dittert et al., 2005). Urea is hydrolyzed in soil to NH$_4^+$, which is then oxidized by nitrifiers (Burton and Prosser, 2001). It can be speculated that using another form of N fertilizer, for example, KNO$_3$, would greatly reduce the production of N$_2$O in the studied agricultural system.

In our study, the emission of N$_2$O was lower in PBs than in CBs, in both cases with residue retention. Tillage can increase the emission of N$_2$O (Baggs et al., 2003; Ussiri et al., 2009), have no effect on N$_2$O emission at all (Jantalia et al., 2008), or decrease the emission of N$_2$O compared with no-till (Robertson et al., 2000; Almaraz et al., 2009a). For instance, Ussiri et al. (2009) reported that the emission of N$_2$O was 1.82 kg N/ha/year in a chisel till treatment and 1.96 kg N/ha/year in a moldboard plow till treatment but only 0.94 kg N/ha/year in the no-till system. The emission of N$_2$O is the result of so many interacting processes that it is difficult to predict how no-till will affect it compared with conventional till. It can be assumed that lower temperatures and less compact soils in no-till than in conventional till will reduce emissions of N$_2$O, whereas larger soil organic matter content, high moisture content, and high mineral N content will favor emissions of N$_2$O.

Retaining the crop residues in PBs had no effect on the emission of N$_2$O compared with PBs with crop removal. Although fertilizer applications are the largest contributors to the emission of N$_2$O in soil, that is, 35% as estimated for Canada, the contribution of crop residues is also substantial, that is, 24% (Rochette et al., 2008). Retaining crop residue might increase emissions of N$_2$O (Singh et al., 2008), but its effect will depend on type of crop, biochemical quality of the residue, agricultural management, and climatic and soil conditions (Novoa and Tejeda, 2006). In our study, immobilization of mineral N when the crop residue was retained might have reduced emissions of N$_2$O.

**Fluxes of Methane**

The fluxes of CH$_4$ were low and variable in this study, and no clear pattern emerged from it (Figure 15.3c). Soil temperature and moisture content were not significantly correlated with emissions of CH$_4$, except for water content in CBs (Table 15.5). Elder and Lal (2008) also reported that both CH$_4$ uptake and emission were low when comparing moldboard/disking, no-till, and bare treatments.
The emission of CH$_4$ was significantly affected by tillage. PBs were a sink for CH$_4$, whereas CBs were a source. Ussiri et al. (2009) reported similar results. They found that soil in the no-till system was a sink of 0.32 kg CH$_4$-C/ha/year but a source of 2.27 kg CH$_4$-C/ha/year in the chisel till and 2.76 kg CH$_4$-C/ha/year in the moldboard plow till. However, Omonode et al. (2007) reported that chisel and moldboard plow resulted in a low CH$_4$ uptake, 7.6 and 2.4 kg CH$_4$-C/ha/year, respectively, whereas no-till resulted in net emissions of 7.7 kg CH$_4$-C/ha/year. Soils can be a net sink or source of CH$_4$ depending on different factors, such as moisture, N level, organic material application, and type of soil (Gregorich et al., 2005). Methane is consumed by soil methanotrophs, which are ubiquitous in many soils (McLain and Martens, 2006), and is produced by methanogenic microorganisms under anaerobic soil conditions (Chan and Parkin, 2001). Agricultural systems usually are not a large source or sink of CH$_4$ (Chan and Parkin, 2001). They are only sources of CH$_4$ after application of manure or other organic materials (Johnson et al., 2007), although crop residue management had no significant effect on CH$_4$ emission in this study. It can be assumed that the emission of CH$_4$ was controlled more by soil structure and less by available organic matter. PB soil is better structured than soil in the CB system, as in the latter the beds are formed every year (Verachtert et al., 2009). As such, the diffusion of CH$_4$ in CB soil was inhibited, and hence its oxidation. Additionally, more anaerobic microsites might have been formed in CBs as O$_2$ diffusion was inhibited. Under anaerobic conditions, CH$_4$ was produced, increasing its emission. As such, tillage damages CH$_4$ oxidation sites, thereby reducing the CH$_4$ oxidation capacity of soils (Lessard et al., 1994).

**Global Warming Potential of Different Agricultural Systems**

The emission of N$_2$O contributed to GWP, whereas CH$_4$ emission reduced it. The contribution of CH$_4$, however, to the GWP of GHGs was small, <2% of that of N$_2$O. Robertson, Paul, and Harwood (2000) found that the contribution of CH$_4$ to the GWP of GHGs was <10 times that of N$_2$O. The difference in GWP between PBs and CBs caused by GHG emissions was 284 kg CO$_2$/ha/year. Nouchi and Yonemura (2005) reported that no-till could decrease GHG emissions (CO$_2$, N$_2$O, and CH$_4$) in C equivalents with 1830 kg C/ha/year compared with conventional tillage. Ussiri et al. (2009) found that GWP associated with N$_2$O and CH$_4$ in no-till might decline by 50% compared with moldboard and chisel tills (Ussiri and Lal, 2009). However, Oorts et al. (2007) reported that no-till systems emitted more GHGs (CO$_2$ and N$_2$O) on an annual basis than a conventional system. There are different explanations for the different effects of no-till and conventional tillage on the GWP of GHGs. First, the length of the experiment is important. The experiment described by Ussiri and Lal (2009) and Ussiri et al. (2009) was a 43 year study, whereas the study reported here was only a 10-year study. Six et al. (2004) reported a strong time dependency in the GHG mitigation potential of no-till. Second, the environmental conditions, that is, rainfall and temperature, are important. The study reported here was conducted under semiarid conditions with relatively low temperature fluctuations, whereas most other studies were done in temperate regions with large differences in temperatures between winter and summer. Third, soil and crop characteristics also affect GHG emissions. Fourth, tillage system and crop residue management will also affect GHG emissions. Removal of crop residues reduced the effect of GHGs on GWP in PBs with 36 kg CO$_2$/ha/year. Fifth, the type and timing of N fertilizer application will affect emissions of GHG. The emission of N$_2$O in our system was strongly correlated with the concentrations of NH$_4^+$ and NO$_3^-$, so a controlled application of urea might reduce the emission of N$_2$O and thus the GWP of the systems studied.

Considering the 0–60 cm soil layer, 1386 kg/ha/year more CO$_2$ was sequestered in the PB system than in the CB system with residue retention. As such, the contribution of organic C in the soil to net GWP was more important than that of the GHG emissions in the studied agricultural systems. Removing crop residues from PBs increased net GWP considerably, with 6801 kg CO$_2$/ha/year nearly completely attributable to a reduced amount of organic C in the 0–60 cm layer. Remaking
the beds in CB plots with residue retention increased net GWP, with approximately 1643 kg CO$_2$/ha/year compared with PB plots with residue retention mainly attributable to the increased sequestration of C in soil. This shows that PBs with crop residue retention can be an important tool to reduce the GWP of agriculture in the central highlands of Mexico. However, it might be difficult to convince farmers to retain the crop residue in the field as it is often used as feed for animals.

**SUMMARY AND CONCLUSION**

Organic matter content increases in soil with no-tilled permanent raised beds (PBs) compared with soil with conventionally tilled beds (CBs), and this might affect GHG emissions. GHG (CO$_2$, N$_2$O, and CH$_4$) emissions were measured from PBs from which crop residue was either removed or retained and from CBs where crop residue was retained. The CO$_2$ emission was not affected by tillage, but CH$_4$ and N$_2$O emissions were lower in PBs when residue was retained than in CBs. Removing crop residue from PBs reduced CO$_2$ emission compared with when it was retained, but it had no effect on N$_2$O and CH$_4$ emissions. The GWP of GHG emissions was higher in CBs (801 kg CO$_2$/ha/year) than in PBs (517 kg CO$_2$/ha/year) with crop residue retention, but more C was sequestered in the 0–60 cm soil layer in PBs (83.4 Mg C/ha) than in CBs (79.2 Mg C/ha). Crop residue removal in PBs had little effect on the GWP of GHG compared with PBs with crop residue retained, but less C was sequestered in the latter (63.1 Mg C/ha). Net GWP (considering soil C sequestration, GHG emissions, fuel used, glyphosate application, fertilizer and seed production) was lower in CBs with crop residue retention (1062 kg CO$_2$/ha/year) than in PBs with crop residue removal (6120 kg CO$_2$/ha/year), but it was larger than in PBs with crop residue retention (~681 kg CO$_2$/ha/year).

We found that reduced tillage when beds were made permanent and crop residue retention greatly reduced net GWP compared with when beds were tilled and remade each year.

We found that retention of crop residue in PBs increased the emission of CO$_2$ compared with where it was removed, but tillage did not affect fluxes of CO$_2$. Emission of CH$_4$ and N$_2$O was larger from CBs than from PBs, but crop residue management in PBs had no significant effect on fluxes of CH$_4$ and N$_2$O. Concentrations of mineral N were larger in CBs than in PBs, whereas the removal of crop residue from PBs increased mineral N concentration. Soil temperature was higher in CBs than in PBs and in PBs with crop residue retained compared with where it was removed. Soil water was better preserved in PBs than in CBs and in PBs where residue was retained than where it was removed.

The higher water content in the PB compared with the CB will favor plant growth during dry spells. However, retaining crop residues in PBs will require sufficient application of inorganic N, as mineral N in soil is lower in PBs than in CBs or PBs with crop residue removed. Limited N availability in PBs with crop residue retained might reduce yields as poor farmers in the central highlands of Mexico apply little or no N fertilizer.

Reduced tillage on PBs and crop residue retention strongly reduced the net GWP of the system compared with the case when beds were remade each year. PBs with residue retention reduced net GWP by 50% compared with CBs with residue retention, but the removal of residues from the PBs more than doubled it.

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