



Greenhouse gas emissions under conservation agriculture compared to traditional cultivation of maize in the central highlands of Mexico

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ABSTRACT

In 1991, the 'International Maize and Wheat Improvement Center' (CIMMYT) started a field experiment in the rain fed Mexican highlands to investigate conservation agriculture (CA) as a sustainable alternative for conventional maize production practices (CT). CT techniques, characterized by deep tillage, monoculture and crop residue removal, have deteriorated soil fertility and reduced yields. CA, which combines minimum tillage, crop rotations and residue retention, restores soil fertility and increases yields. Soil organic matter increases in CA compared to CT, but increases in greenhouse gas emissions (GHG) in CA might offset the gains obtained to mitigate global warming. Therefore, CO₂, CH₄ and N₂O emissions, soil temperature, C and water content were monitored in CA and CT treatments in 2010–2011. The cumulative GHG emitted were similar for CA and CT in both years, but the C content in the 0–60 cm layer was higher in CA (117.7 Mg C ha⁻¹) than in CT (69.7 Mg C ha⁻¹). The net global warming potential (GWP) of CA (considering soil C sequestration, GHG emissions, fuel use, and fertilizer and seeds production) was $-7729 \text{ kg CO}_2 \text{ ha}^{-1} \text{ y}^{-1}$ in 2008–2009 and $-7892 \text{ kg CO}_2 \text{ ha}^{-1} \text{ y}^{-1}$ in 2010–2011, whereas that of CT was 1327 and 1156 kg CO₂ ha⁻¹ y⁻¹. It was found that the contribution of CA to GWP was small compared to that of CT.

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1. Introduction

Cultivation of maize (*Zea mays* L.) started nearly 9000 y ago in Mexico (Ranere et al., 2009) and is still the staple crop for most of its people. In the highland valleys of the developing world, approximately 6.2×10^6 ha are cultivated with maize (Beck and Torres, 2003), with ca. 2×10^6 ha being cultivated in Mexico, mainly in the states of Mexico, Puebla, Tlaxcala and Hidalgo with mean yields $< 2 \times 10^3 \text{ kg ha}^{-1}$ (Eliás-Calles et al., 2003).

Traditional and widely used cultivation techniques consist in monoculture of often traditional maize varieties, low N fertilizer application rates, no or little irrigation, removal of crop residue for animal feed or fuel, and little or no use of herbicides and pesticides. This tillage based cultivation technique has resulted in degraded unstructured soil prone to wind and water erosion with low organic matter and nutrient content (Govaerts et al., 2008).

In 1991, the 'International Maize and Wheat Improvement Center' (CIMMYT) started a field experiment to investigate conservation agriculture options, i.e. the combination of reduced or zero tillage, crop

residue retention and crop rotation, as a sustainable alternative for the conventional practices. In this study, two treatments of the experiment were compared: conservation agriculture (CA), i.e. zero tillage with crop residue retained and maize (*Z. mays* L.)–wheat (*Triticum aestivum* L.) rotation, and the conventional technique (CT) in the central highlands of Mexico, i.e. conventional tillage where the crop residue was removed and maize monoculture (in order to not confound fertilization was kept constant). Based on this long-term experiment the authors have already described the long-term effects of tillage, residue management, and crop rotation on crop yield, on physical and chemical soil quality, on root rot and nematode populations, plus the interactions and effects on yield of root rot, nematodes, and water dynamics and infiltration (Govaerts et al., 2007). Zero tillage with residue retention and crop rotation (CA) resulted in a soil with good physical, chemical and biological qualities, and high, stable crop yields, compared to conventional practices (Govaerts et al., 2005; 2006). Averaged over 1997–2009, maize grain yields were 50% higher in CA than in CT: 5.34 Mg ha^{-1} in CA and 3.53 Mg ha^{-1} in CT. Additionally, CA showed more resilience to drought than CT (Verhulst et al., 2011). Organic C in the top soil increases often, so CA has the potential to sequester more C than conventional agriculture thereby mitigating global warming. However, increased organic matter in soil can stimulate emissions of the greenhouse gas (GHG)

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carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) thereby negating the positive effects of more C being sequestered in soil (Li et al., 2005). Additionally, an increased C content in the top soil in CA can be compensated by a decrease of C in the deeper soil layers (VandenBygaert and Angers, 2006).

The effect of tillage and crop residue management on the net global warming potential (GWP) (taking into account soil C sequestration, emissions of GHG from soil and fuel used for farm operations, and the production of fertilizer and seeds) was investigated at CIMMYT's long-term field experiment started in 1991 for two years, i.e. 2008–2009 and 2010–2011. Alternating years were monitored so that CA was both times cultivated with maize. The net GWP of the two agricultural systems, i.e. conservation agriculture (no-tillage, crop residue retention and wheat–maize crop rotation) and conventional agriculture (tillage, crop residue removal and maize monoculture) was compared and the potential of conservation agriculture to mitigate global warming determined.

2. Material and methods

2.1. Characterization of the El Batán experiment station

The El Batán research station at 2249 masl is located near the former lake Texcoco (19.318 N; 98.508 W), situated in the semi-arid, subtropical highlands of Central Mexico. The slope of the field at the experimental station is <0.3%. The mean maximum and minimum temperatures are 24 and 6 °C, respectively (1991–2009) and the average annual rainfall is 625 mm y⁻¹, with approximately 545 mm falling between May and October. Short, intense rain showers followed by dry spells typify the summer rainy season and the total yearly potential evapotranspiration of 1550 mm exceeds annual rainfall. The El Batán experiment station has an average growing period of 132 days (FAO, 1978).

The soil is classified as a Haplic Phaeozem (Clayic) in the World Reference Base system (IUSS. Working Group WRB, 2006) and as a fine, mixed, thermic Cumulic Haplustoll in the USDA Soil Taxonomy system (Soil Survey Staff, 2003). The soil is characterized by good chemical and physical conditions for farming and the major limitations are periodical drought, periodical water excess and wind and water erosion.

2.2. Description of the field experiment

A long-term rain-fed experiment was started in 1991 with the size of the plots 7.5 × 22 m. The experimental design consisted of 32 management practices in duplicate in a randomized complete block. Details of the experimental design, planting, weed control and fertilizer application can be found in Govaerts et al. (2005). Only two management practices, CA i.e. zero tillage with crop residue retained and maize (*Z. mays* L.) wheat (*Triticum aestivum* L.) rotation, and CT in the central highlands of Mexico, i.e. conventional tillage where the crop residue was removed and maize monoculture, were monitored in this study. The amount of organic C that was left in the field in both treatments is given for the period 1996–2006 (Table 1). In 2008, maize was planted in both CT and CA on May 30, while in 2010 maize was planted on June 15 in 2010 and harvested at the end of October.

Maize planting and fertilizer application were done in one pass with the same machine. In the CT treatment, the tillage operations after harvest consisted of one pass with a chisel plough to 30 cm depth, followed by two passes with a disk harrow to 20 cm depth and two passes with a spring teeth harrow to 10 cm. The spring teeth harrow was used when needed for weed control (typically twice) during the dry season. To prepare the seed bed in May, the tillage operations of December were repeated (but with only one pass with the spring teeth harrow). In the CA treatment, weed control during the dry season was done with glyphosate.

Table 1

The amount of organic C (Mg ha⁻¹) that was left in the field with zero-till, residue retention and wheat–maize crop rotation (CA), and conventional tillage with crop removal and maize monoculture (CT) between 1996 and 2006.

Year	CT (Mg ha ⁻¹)	CA (Mg ha ⁻¹)
1996	1.80	8.87
1997	2.71	7.83
1998	2.36	10.83
1999	0.48	6.54
2000	2.34	10.40
2001	0.85	8.86
2002	2.35	11.83
2003	1.16	9.74
2004	1.43	10.27
2005	2.48	10.24
2006	2.30	9.38

2.3. Measurement of the greenhouse gas emissions

In the first year, the monitoring of fluxes of the GHG started before planting on the 19th of May 2008 and ended before the next crop cycle on the 13th of May 2009. The second year sampling started on the 31st of May 2010 and ended on 24th of May 2011 also before the next crop cycle. The emissions of CO₂, CH₄ and N₂O were measured simultaneously. In 2008–2009 four chambers were placed in each plot and in 2010–2011 three chambers and used to determine the fluxes of the GHG. The chambers had a length of 25 cm and an inner diameter of 20 cm and were designed with a coated top and a sampling port with a butyl rubber stopper (Parkin et al., 2003). The chambers were inserted 5 cm into the soil so that the height from the soil surface to the top of the chamber was 20 cm. At sowing, the chambers were removed and were inserted into the soil in the same place after sowing. At harvest and tillage, this procedure was repeated. The gas sampling was done between 9:00 and 11:00 am. At sampling, covers were placed on the chamber and sealed air-tight with Teflon tape. Zero, 20, 40 and 60 min after the chamber was sealed, 15 cm³ air was injected into the PVC chamber headspace, while the gas was mixed by flushing at least 3 times with the air inside the chamber followed by gas collection for analysis. The 15-cm³ air sample was injected into 15-cm³ evacuated vials closed with a butyl rubber stopper and sealed with an aluminum cap pending analysis.

The vials were analyzed for CO₂ and N₂O on an Agilent Technology 4890D gas chromatograph (GC) fitted with an electron capture detector (ECD). The CH₄ of the vials was analyzed on an Agilent Technology 4890D gas chromatograph fitted with a flame ionization detector (FID). Details of the columns used to separate the gasses and the settings of the GCs can be found in Ruíz-Valdiviezo et al. (2010).

2.4. Soil sampling and soil analysis

Soil was sampled for mineral N, i.e. NH₄⁺, NO₂⁻ and NO₃⁻ and water content, when GHG emissions were determined. Four soil cores were taken from the 0–20 cm soil layer at random. Two samples were taken in the opposite corners of the plot and pooled to give two composite samples. Two sub-samples of 20 g soil from each of the two samples taken at the two treatments were added to 250 ml bottles and extracted for NH₄⁺, NO₂⁻ and NO₃⁻ with 100 ml 0.5 M K₂SO₄ filtered through Whatman® filter paper number 42 and stored at –20 °C pending analysis. The rest of the samples was weighed and dried for 24 h at 105 °C. Oven dry weight was then determined and gravimetric water content calculated and converted to volumetric water content by multiplying with bulk density. Air temperature was determined between 9 and 11 am while the soil temperature was determined at a depth of 10 cm with a thermometer at the same time.

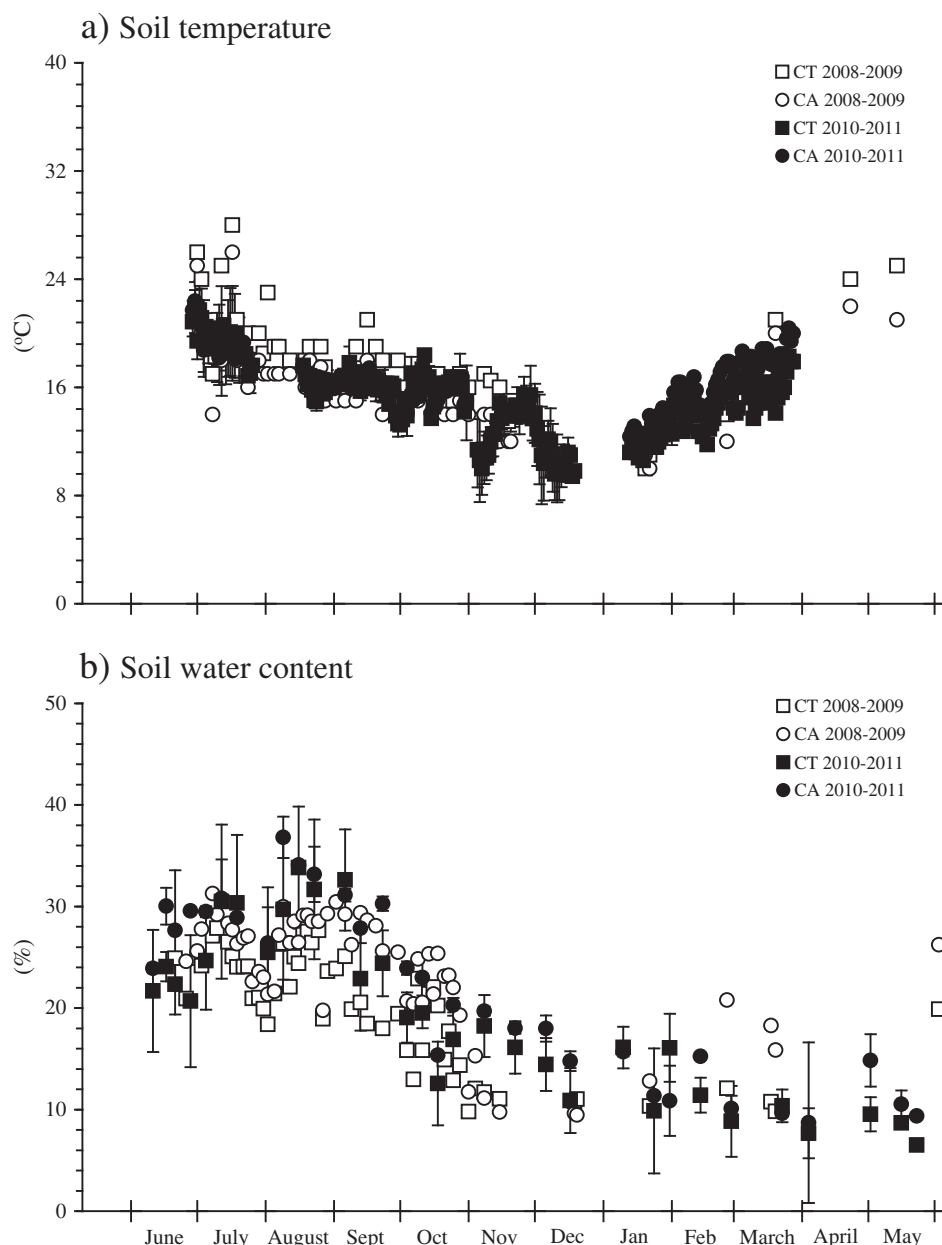


Fig. 1. a) Soil and air temperature (°C) and b) volumetric water content (%) at 'El Batán' from the June 2008 until the middle of May 2009 and from the end of May 2010 until the end of May 2011 with conventional technique (conventional tillage with crop removal and maize monoculture; CT, ○) and conservation agriculture (zero tillage with crop retention and wheat maize rotation; CA, ●). Bars are \pm one standard deviation.

After harvest, samples were taken from the 0–20, 20–40 and 40–60 cm layers in four points in each plot to determine total C and bulk density. A core sampler 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 remaining soil was used for the determination of total C. Details of the methods used to measure total C and N and concentrations of NH_4^+ , NO_2^- and NO_3^- in the K_2SO_4 extracts can be found in Ruíz-Valdiviezo et al. (2010). In all methods used to characterize the soil, internal standards were included.

2.5. Global warming potential

Calculation of the net GWP was based on Robertson et al. (2000) and Thelen et al. (2010), taking into account soil C sequestration (Δ

soil C GWP), emissions of GHG from soil (soil N_2O flux + soil CH_4 flux), emissions of GHG from fuel used for farm operations (tillage, glyphosate application, planting and fertilizer application, harvest) (operation GHG flux) and the production of fertilizer and seeds (input GHG flux). The net GWP was calculated as:

$$\text{Net GWP} = \Delta\text{soil C GWP} + \text{soil N}_2\text{O flux} + \text{soil CH}_4\text{flux} + \text{operation GHG flux} + \text{input GHG flux}.$$

The C sequestered (expressed as CO_2) in the soil on a yearly basis was calculated by taking the difference in soil organic carbon stocks between CT and CA and dividing by the number of years after the experiment was started, i.e. 20 y. The emissions associated with agronomic inputs and farming operations were calculated from values reported by West and Marland (2002). Planting and fertilizer application were done in one pass with the same machine, so fertilizer application was not counted separately. The same values were used for

Table 2

The effect of zero-till with residue retention and wheat–maize crop rotation (CA), and conventional tillage with crop removal and maize monoculture (CT) on soil temperature (°C), volumetric water content (%), fluxes of CO₂ (kg C ha⁻¹ d⁻¹), N₂O (g N ha⁻¹ d⁻¹) and CH₄ (g C ha⁻¹ d⁻¹), mineral N (NH₄⁺, NO₂⁻ and NO₃⁻) in the 0–20 cm layer, and total cumulative CO₂, N₂O and CH₄ emitted (kg equivalent CO₂ ha⁻¹ y⁻¹) between 19th of May 2008 and 13th of May 2009, and 31st of May 2010 and 24th of May 2011.

Characteristic	2008–2009		2010–2011		Year		Treatment		Year × treatment	
	CT	CA	CT	CA	F value	P value	F value	P value	F value	P value
Soil temperature (°C)	20.0	17.1	15.8	16.7	85.61	<0.0001	36.47	<0.0001	14.18	0.0001
Volumetric water content (%)	19.9	23.6	18.5	21.0	4.36	0.0379	9.98	0.0018	0.35	0.5537
NH ₄ ⁺ concentration (mg N kg ⁻¹ soil)	8.1	5.1	16.4	15.5	2.97	0.0861	0.13	0.7183	0.04	0.8483
NO ₂ ⁻ concentration (mg N kg ⁻¹ soil)	0.45	0.56	0.39	0.35	7.90	0.0054	0.74	0.3898	2.39	0.1237
NO ₃ ⁻ concentration (mg N kg ⁻¹ soil)	19.7	12.9	11.9	11.0	5.42	0.0208	3.12	0.0785	1.89	0.1705
Mineral N (mg N kg ⁻¹ soil)	28.2	18.6	29.2	26.9	0.41	0.4763	0.85	0.3567	0.33	0.5681
Fluxes of CO ₂ (kg C ha ⁻¹ d ⁻¹)	6.50	7.01	2.52	2.12	ND ^a	ND	0.01	0.9237	ND	ND
Fluxes of N ₂ O (g N ha ⁻¹ d ⁻¹)	4.92	5.19	2.35	2.03	ND	ND	0.01	0.9204	ND	ND
Fluxes of CH ₄ (g C ha ⁻¹ d ⁻¹)	-1.37	-1.68	-2.41	-1.37	ND	ND	0.17	0.7186	ND	ND
CO ₂ emission (kg equivalent CO ₂ ha ⁻¹ y ⁻¹)	5483	5569	2607	2443	93.61	0.0105	0.08	0.8078	0.16	0.7261
CH ₄ emission (kg equivalent CO ₂ ha ⁻¹ y ⁻¹) ^b	-22	-20	-21	-13	0.04	0.8654	0.12	0.7622	0.03	0.8877
N ₂ O emission (kg equivalent CO ₂ ha ⁻¹ y ⁻¹) ^b	425	422	254	252	16.13	0.0568	0.00	0.9712	0.00	0.9859

^a ND: not determined.

^b The CO₂-equivalent emission for N₂O was 298, 25 for CH₄ and 1 for CO₂ (IPCC, 2007).

chisel and disk ploughing. The C emission for a spring tooth harrow pass was counted as half of a disk plough pass. 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 emission of 298 for N₂O and 25 for CH₄ (IPCC, 2007).

2.6. Statistical analysis

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

Soil characteristics, i.e. water content and temperature, the C content in the 0–20, 20–40, 40–60 and 0–60 cm layers and concentration of NH₄⁺, NO₂⁻ and NO₃⁻ were subjected to a two-way analysis of variance using PROC GLM (SAS, 1989) to test for significant differences between treatment (CA versus CT), year (2008–2009 and 2010–2011) and their interaction. Significant differences between treatments CO₂, CH₄ and N₂O emission rates were determined using PROC MIXED considering repeated measurements (SAS, 1989).

The total emissions of CO₂, N₂O and CH₄ over the two periods, i.e. 19th May 2008 until 13th May 2009 and 31st May 2010 until 24th of May 2011, were calculated by linear interpolation of data points between each successive sampling event including the five missing days until the 18 of May 2009 and 30th of May 2011 (Ussiri et al., 2009) and numerical integration of underlying area using the trapezoid rule (Whittaker and Robinson, 1967). Total emissions of CO₂, N₂O and CH₄ were subjected to analysis of variance using PROC GLM (SAS, 1989) to test for significant differences between treatment (CA versus CT), year (2008–2009 and 2010–2011) and their interaction.

Table 3

The effect of zero-till with residue retention and wheat–maize crop rotation (CA) and conventional tillage with crop removal and maize monoculture (CT) on total C content of the 0–20 cm, 20–40 cm, 40–60 cm and 0–60 cm layers (Mg C ha⁻¹).

Characteristic	CA	CT	MSD ^a	F value	Pr > F
C content 0–20 cm layer (Mg C ha ⁻¹)	40.0	22.9	3.6	94.36	<0.0001
C content 20–40 cm layer (Mg C ha ⁻¹)	33.1	24.2	2.8	41.57	<0.0001
C content 40–60 cm layer (Mg C ha ⁻¹)	32.3	22.6	4.0	24.44	<0.0001
C content 0–60 cm layer (Mg C ha ⁻¹)	117.7	69.7	8.1	146.36	<0.0001

^a MSD: minimum significant difference ($P < 0.05$).

3. Results and discussion

3.1. Soil temperature, water and carbon content

The minimum soil temperature of 9.4 was reached in December 2010 and the maximum in both June 2008 and July 2009 (Fig. 1a). In 2008–2009, the average soil temperature was higher in CT than in CA, but in 2010–2011 the opposite was observed ($P < 0.0001$) (Table 2). The volumetric water content was high in June, July and August of 2008 and 2010 and decreased thereafter (Fig. 1b). In 2009, the soil water content increased again in March especially in the CA treatment, but in 2011 it further decreased until May. The mean volumetric soil water content was significantly lower in CT than in CA and in 2008–2009 than in 2010–2011, while the interaction between treatment and year was not significant (Table 2).

Crop residue retained on the soil surface isolates the soil from heating up and reflects solar radiation (Shinners et al., 1993). Consequently maximum temperatures are lower and minimum temperatures are higher in CA compared to CT. Crop residue retained on the soil surface forms a barrier against evaporation and prevents runoff and wind erosion (Ussiri and Lal, 2009). Crop residue retained on the top soil, also improves water holding capacity and soil aggregate stability thereby facilitating water infiltration and preventing soil drying (Zibilske and Bradford, 2007). Tillage increases soil packing and breaks soil structure so that precipitation infiltrates more rapidly in conservation agriculture than in conventional systems reducing water losses by run-off (Licht and Al-Kaisi, 2005).

The C content was significantly larger in the 0–20 cm, 20–40 cm and 40–60 cm layers of CA compared to CT and the effect was more outspoken in the 0–20 cm layer than in the 20–40 and 40–60 cm layers ($P < 0.0001$) (Table 3). The C content in the 0–60 cm layer was significantly larger in the CA compared to CT ($P < 0.0001$).

The soil organic C (SOC) was 1.8 times higher in the 0–20 cm layer of CA compared to CT and 1.7 times in the 0–60 cm layer. Approximately 5-times more organic C is left in the field in CA than in CT from 1996 to 2006 (Table 1). Consequently, the SOC is larger in CA than in CT. Even larger increases have been reported. Ussiri and Lal (2009) found that no-till increased the total soil organic C in the 0–15 cm layer 2.7 times compared to chisel till and 2.9 times compared to moldboard plow till. Organic matter often increases in the 0–5 cm soil layer of no-tilled soil compared to conventionally tilled soil (Sombrero and de Benito, 2010; Sainju et al., 2011). Removing residue in CT reduces the soil organic matter content as the mineralized soil organic material is not replenished. Additionally, minimal-till in CA favors stable aggregates physically protecting organic matter thereby reducing mineralization rates (Lichter et al., 2008). In CT,

tillage breaks up soil aggregates so that organic matter becomes available for decomposition (Six et al., 2000; Bronick and Lal, 2004).

Although the soil organic C was larger in the 0–20 cm layer of the CA than in the CT, the opposite has been found in the deeper soil layers (VandenBygaart and Angers, 2006). It has been speculated that incorporating crop residue accelerated its mineralization in the top soil, but ploughing moved it downwards where it was protected against mineralization. As a result, the soil organic matter content is similar in both systems when the whole soil profile is considered. However, in our study the soil organic C in CA was larger in each of the three soil layers, i.e. 0–20, 20–40 and 40–60 cm, compared to CT. As such, the beneficial effect of CA on the soil organic matter content was evidenced over the 0–60 cm soil profile.

The total C in the 0–60 cm layer was 117.7 Mg C ha⁻¹ in CA and 69.7 Mg C ha⁻¹ in CT (Table 3). Ussiri and Lal (2009) also found an increase in total C in no-till compared to tilled soil. They reported 60.3 Mg C ha⁻¹ in the 0–15 cm layer and 19.7 Mg C ha⁻¹ in the 15–30 cm layer, i.e. a total of 79.9 Mg C ha⁻¹ in the 0–30 cm layer, after 43 y of no-till, but values of 44.8 Mg C ha⁻¹ for chisel till and 45.3 Mg C ha⁻¹ for moldboard till.

Although retaining the crop residue on the soil surface has many advantages, one of the possible disadvantages is that it will induce N immobilization. Wheat and even more so maize have a high C-to-N ratio, i.e. 24 for wheat and 35 for maize straw, which will induce immobilization of N when the crop residue is mineralized (Verachtert et al., 2009). The soil was fertilized at the experimental site so no

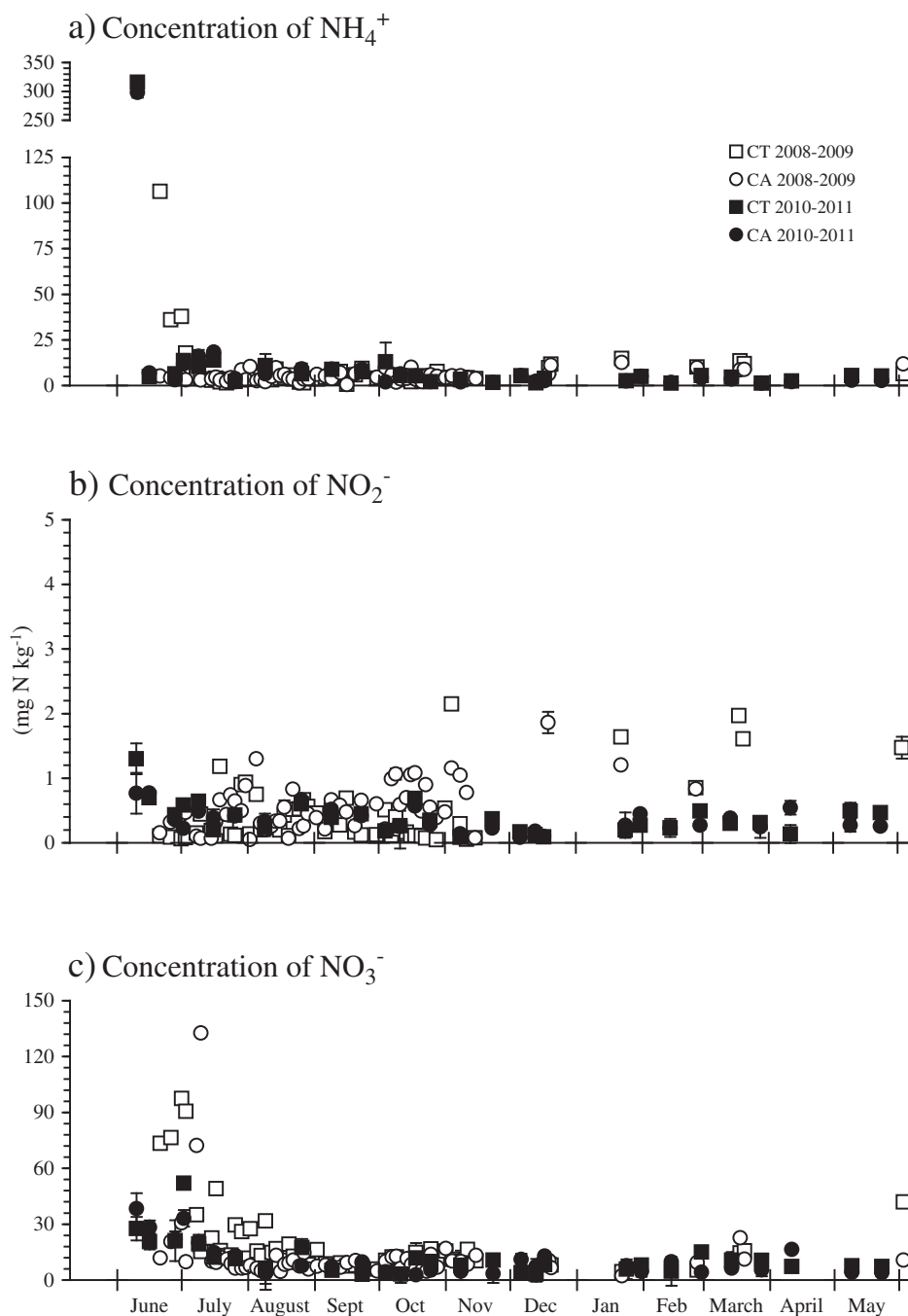


Fig. 2. a) Concentration of ammonium (NH₄⁺), b) nitrite (NO₂⁻) and c) nitrate (NO₃⁻) (mg N kg⁻¹ dry soil) in soil at 'El Batán' from the middle of May 2008 until the middle of May 2009 and from the end of May 2010 until the end of May 2011. Legends to the figures can be found in Fig. 1. Bars are ± one standard deviation.

significant difference in soil mineral N was observed, but it can be speculated that without the application of N fertilizer, the soil will be N deficient potentially reducing crop yield.

3.2. Soil mineral N content

The concentration of NH_4^+ was high just after the application of urea, but remained generally $<20 \text{ mg NH}_4^+ \text{-N kg}^{-1}$ in both 2008–2009 and 2010–2011 (Fig. 2a). The concentration of NH_4^+ was not affected significantly by treatment, year or the interaction between them (Table 2).

The concentration of NO_2^- was variable over time, but remained below $2.5 \text{ mg NO}_2^- \text{-N kg}^{-1}$ in both 2008–2009 and 2010–2011 (Fig. 2b). The concentration of NO_2^- was not affected significantly by treatment, year or the interaction between them (Table 2).

The concentration of NO_3^- was high in June and July after the application of urea with higher concentration found in 2008 than 2010 (Fig. 2c). Later on, amounts of NO_3^- remained generally $<30 \text{ mg NO}_3^- \text{-N kg}^{-1}$. The concentration of NO_3^- was significantly lower in 2010–2011 than in 2008–2009, but was not affected significantly by treatment or the interaction between treatment and year (Table 2).

3.3. Fluxes of CO_2 , CH_4 and N_2O

Fluxes of CO_2 were often higher in June, July and August than in the rest of the year, although some high emissions were detected between January and May in both 2009 and 2011 (Fig. 3a). The flux of CO_2 averaged over the period from 19th of May 2008 to 18th of May 2009 and 31st of May 2010 until 24th of May 2011 was not

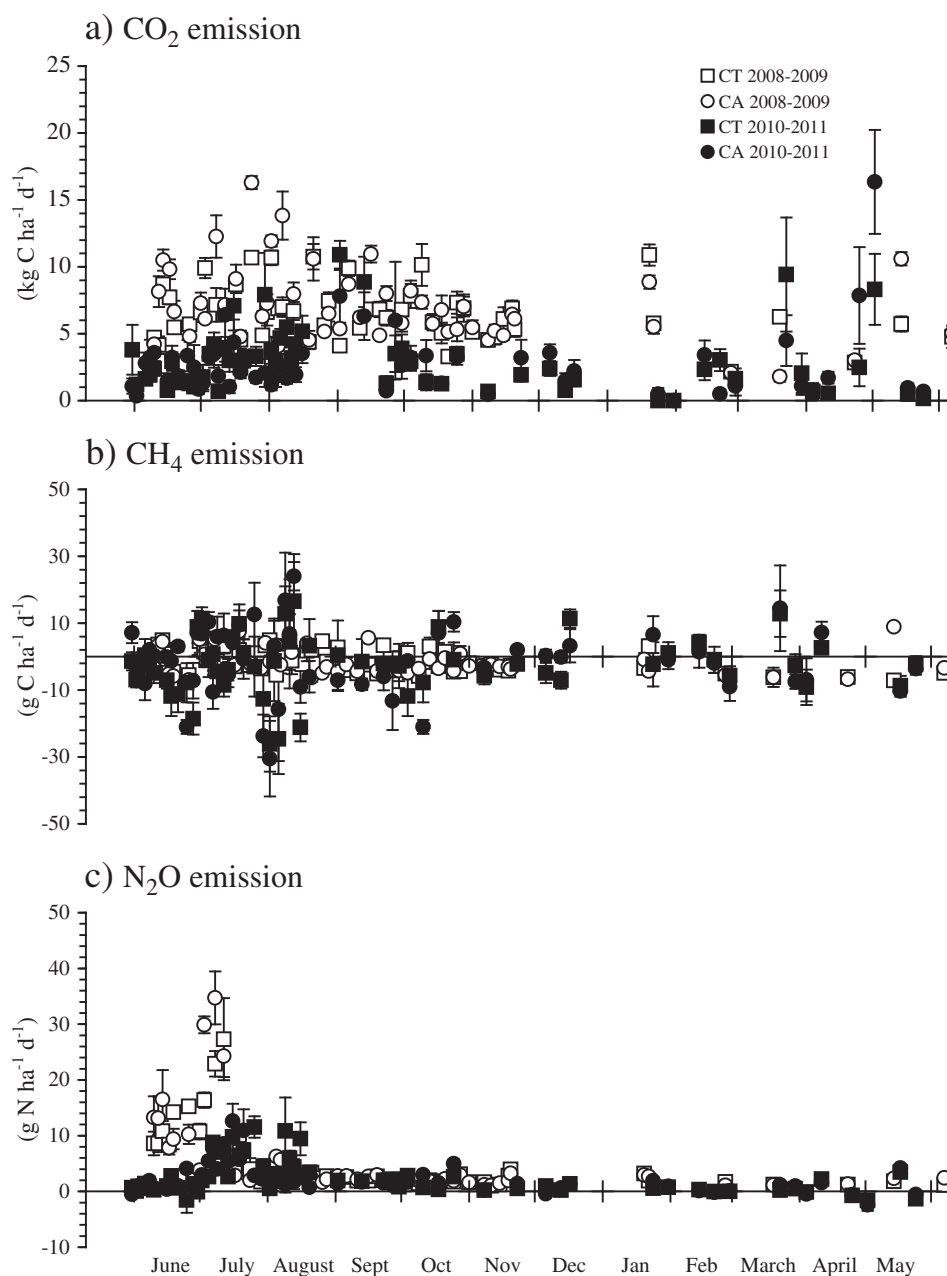


Fig. 3. a) Emission of carbon dioxide (CO_2) ($\text{kg C ha}^{-1} \text{ d}^{-1}$), b) methane (CH_4) ($\text{g C ha}^{-1} \text{ d}^{-1}$) and c) nitrous oxide (N_2O) ($\text{g N ha}^{-1} \text{ d}^{-1}$) in soil at 'El Batán' from the middle of May 2008 until the middle of May 2009 and from the end of May 2010 until the end of May 2011. Legends to the figures can be found in Fig. 1. Bars are \pm one standard deviation.

Table 4

Pearson correlation coefficients between emissions of CO₂ (mg C kg⁻¹ h⁻¹), CH₄ (μg C kg⁻¹ h⁻¹) and N₂O (μg N kg⁻¹ h⁻¹) and soil temperature (°C), concentrations of mineral N (NH₄⁺, NO₂⁻ or NO₃⁻) (mg N kg⁻¹ dry soil) and water content (WC, g kg⁻¹) for conservation agriculture (zero tillage with crop residue retention and wheat–maize crop rotation, CA) and conventional agriculture (tillage, crop residue removal and maize monoculture, CT).

Characteristic	Water content	Temperature	Concentration of			Emission of	
			NH ₄ ⁺	NO ₃ ⁻	NO ₂ ⁻	CO ₂	N ₂ O
Conventional agriculture (CT)							
Temperature	<0.0001						
NH ₄ ⁺ concentration	0.0965	<0.0001					
NO ₃ ⁻ concentration	0.0069	<0.0001	0.0039				
NO ₂ ⁻ concentration	0.0669	0.0790	0.0008	0.5535			
Emission of CO ₂	0.0005	<0.0001	0.7877	0.0017	0.7438		
Emission of N ₂ O	<0.0001	<0.0001	0.7000	<0.0001	0.3095	<0.0001	
Emission of CH ₄	0.2050	0.8255	0.4419	0.5086	0.5558	0.2756	0.0082
Conservation agriculture (CA)							
Temperature	0.0040						
NH ₄ ⁺ concentration	0.0250	0.0844					
NO ₃ ⁻ concentration	0.0616	0.0235	0.0030				
NO ₂ ⁻ concentration	0.8143	0.1940	0.0630	0.6116			
Emission of CO ₂	0.0016	0.7179	0.9801	0.0816	0.1955		
Emission of N ₂ O	0.0014	0.0053	0.7381	<0.0001	0.7676	<0.0001	
Emission of CH ₄	0.6986	0.0575	0.9709	0.4881	0.9619	0.3376	0.0646

Prob<|r| under Ho: Rho = 0 (CORR Procedure, SAS Institute, 1989).

significantly higher in CA than in CT (Table 2). In CT, the flux of CO₂ was significantly correlated to the volumetric water content, soil temperature, the NO₃⁻ concentration and the N₂O flux, while in CA with the volumetric water content and the N₂O flux ($P < 0.05$) (Table 4). The cumulative CO₂ emitted was not significantly different between CA and CT, but significantly lower in 2010–2011 than in 2008–2009.

Emissions of CO₂ are normally proportional to soil organic C when other conditions are similar. Although the soil organic C content was 1.7 times higher in the 0–60 cm layer of the CA treatment than in the CT, the emission of CO₂ was similar in 2008–2009 and 2010–2011. This suggests that the emission of CO₂ was stimulated in CT and/or inhibited in CA. The stubble that is left on the field in CT is mixed into the soil and becomes immediately available as C substrate for microorganisms and tillage breaks up aggregates so that organic material that is physically stabilized in them is liberated (Six et al., 2000). In CA, crop residue is left on the soil surface and is incorporated mostly into the soil through macrofauna activity, i.e. earthworms or ants, which is often inhibited in the dry season, retarding its decomposition (Dangerfield, 1997). Aggregates are not broken up in CA so micro-aggregates within the macro-aggregates can immobilize a part of the soil organic matter (Lichter et al., 2008). As such, tillage stimulates emissions of CO₂ in CT, while its absence in CA hampers decomposition of organic material.

Fluxes of CH₄ did not show a clear pattern, but fluctuated over time in both treatments (Fig. 3b). Fluxes varied between 25 g CH₄-C ha⁻¹ d⁻¹ in CA in September 2010, while a minimum of –32 g CH₄-C ha⁻¹ d⁻¹ was found in CA in August 2010. The mean flux of CH₄ was not significantly different between CA and CT (Table 2). The emission of CH₄ was correlated significantly with volumetric water content in CA and with the emission of N₂O in CT. The cumulative CH₄ emitted was not significantly different between CA and CT, and between 2008–2009 and 2010–2011 (Table 2).

Overall, oxidation of CH₄ prevailed over production of CH₄. The latter appears only to be important when organic material is added to soil or anaerobic conditions prevail (Johnson et al., 2007).

The fluxes of N₂O were often large in June–August especially in 2009, but afterwards values remained generally <5 g N₂O-N ha⁻¹ d⁻¹ (Fig. 3c). A maximum flux of 37.4 g N₂O-N ha⁻¹ d⁻¹ was detected in CA in July 2008. The mean flux of N₂O was not significantly different between CA and CT (Table 2). In CT and CA, the flux of N₂O was significantly correlated to the volumetric water content, soil temperature, the NO₃⁻ concentration and the emission of CO₂ ($P < 0.05$) (Table 4). The cumulative N₂O emitted was not significantly different between CA and CT, and similar for 2008–2009 and 2010–2011.

It has been reported that increases in soil organic matter when crop residue is left on the field might increase emissions of N₂O negating the gains obtained to mitigate global warming by the C sequestered in soil (Li et al., 2005; Novoa and Tejeda, 2006). Increases in emissions of N₂O are the results of increased dynamics of N in soil. This did not apply for the agricultural system we studied. First, the crop residue left on the field has a high C-to-N ratio stimulating N immobilization, so N cycling will be reduced. Second, the emissions of N₂O were strongly correlated to the concentration of NO₃⁻ in the soil, so it appears that denitrification contributed most to the emissions of N₂O.

3.4. Global warming potential

The GWP due to operations was 94 kg CO₂ ha⁻¹ y⁻¹ in CA and 356 in CT kg CO₂ ha⁻¹ y⁻¹, while 568 kg CO₂ ha⁻¹ y⁻¹ due to inputs, i.e. fertilizer and maize seed production (Table 5). The greenhouse gas (GHG) emissions expressed as kg equivalent CO₂ ha⁻¹ y⁻¹ were similar for CT and CA in both 2008–2009 and 2010–2011 (Table 5). As such, machinery use and the C sequestered in soil defined the difference in GWP between CA and CT. In CA, 8793 kg CO₂ ha⁻¹ y⁻¹ was sequestered in the soil when CT was used as control. The net global warming potential of CA (considering soil C sequestration, GHG emissions, fuel use, and fertilizer and seeds production) was –7729 kg CO₂ ha⁻¹ y⁻¹ in 2008–2009 and

Table 5

The effect of zero tillage with wheat–maize crop rotation and residue retention (CA) and conventional tillage with residue removal and maize monoculture (CT) on total CO₂, N₂O and CH₄ greenhouse emitted between 19th of May 2008 and 13th of May 2009 and 31st of May 2010 and 24th of May 2011 and the net global warming potential.

Characteristic (kg equivalent CO ₂ ha ⁻¹ y ⁻¹)	2008–2009		2010–2011	
	CT	CA	CT	CA
Greenhouse gas emissions	403	402	232	239
Machinery use in the field ^a	356	94	356	94
Agronomic inputs (fertilizer and seed) ^a	568	568	568	568
Soil C sequestration per year ^b	0	–8793	0	–8793
Net global warming potential ^c	1327	–7729	1156	–7892

^a Values taken from West and Marland (2002), but expressed as kg equivalent CO₂ ha⁻¹ y⁻¹.

^b Changes in carbon stock per year since the beginning of the experiment (20 y) calculated with SOC in CT treatment as reference.

^c Net GWP calculated as the sum of C emitted by operations and inputs, GHG emissions and C sequestration (Robertson et al., 2000).

–7892 kg CO₂ ha⁻¹ y⁻¹ in 2010–2011, whereas that of CT was 1327 and 1156 kg CO₂ ha⁻¹ y⁻¹ (Table 5).

The greenhouse gas (GHG) emissions of both systems expressed as kg equivalent CO₂ ha⁻¹ y⁻¹ were similar for CT and CA. Consequently, the most important impact of the agricultural practices applied, i.e. differences between CT and CA, to mitigate global warming is the potential to sequester C in the 0–60 cm soil layer. After nearly 20 y, more C was sequestered in each soil layer of CA than in CT and overall the 0–60 cm layer of CA contained 43.6 Mg C ha⁻¹ more than CT.

Considering fuel use for operations (tillage in CT, planting and fertilizing, harvest) and production of inputs (fertilizer and seed), emissions of greenhouse gases from soil and soil C sequestration, the net global warming potential of CA was negative in both 2008–2009 and 2010–2011 while positive in CT. As such, CA has the potential to reduce global warming while CT contributes to it.

Approximately 2 × 10⁶ ha are cultivated with the conventional technique in the central highlands of Mexico alone, so a net C sequestration of 10⁶ Mg C ha⁻¹ y⁻¹ could be achieved if this area was under CA. However, it might be challenging to implement CA in certain parts of the country. Changing to CA systems will require a change in mindset. Farmers traditionally remove crop residues from the field in Mexico for feed and that, combined with zero tillage, has a negative effect on yields and soil fertility (Govaerts et al., 2005). Therefore, promoting CA systems require complex innovation networks that include promotion of alternative fodder crops and takes into account other socio-economic and biological limitations and catalyzes innovations through appropriate actors of change (Sayre and Govaerts, 2009).

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