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Global warming potential of agricultural systems with contrasting tillage and residue management in the central highlands of Mexico

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ABSTRACT

Conservation agriculture based on (1) minimal soil movement, (2) retention of rational amounts of crop residue, (3) economically viable crop rotations restores soil fertility. Conservation agriculture improves soil characteristics, but it remains to be seen how zero tillage (ZT) affected greenhouse gas emissions (GHG) and the global warming potential (GWP) compared to conventional tillage (CT) when crop residue was kept or removed in a maize-wheat crop rotation since 1991. The soil organic C content in the 0–60 cm layer was larger in ZT (117.7 Mg C ha^{-1}) compared to CT (76.8 Mg C ha^{-1}) when residue was retained, but similar when it was removed. Tillage and residue management had only a small effect on GWP of the GHG emissions. However, the C sequestered in the 0–60 cm was affected by tillage and crop residue management, resulting in a negative net GWP for ZT with crop residue retention (−6.277 Mg CO_2 ha^{-1} y^{-1}) whereas in the other management practices it ranged from 1.288 to 1.885 Mg CO_2 ha^{-1} y^{-1}. It was found that cultivation technique had little effect on the GWP of the GHG, but had a large effect on C sequestered in the 0–60 cm layer and the net GWP.

1. Introduction

Since 1991, the International Maize and Wheat Improvement Center (CIMMYT) has been investigating the effect of tillage, crop residue management and crop rotations under rain-fed conditions on crop yield, physical and chemical soil quality, soil microbial biomass and root rot and nematode populations. Conservation agriculture, i.e. residue retention, zero tillage and crop rotation improves water use efficiency, decreases soil erosion and temperature, improves soil quality and increases yields (Govaerts et al., 2006, 2007, 2008; Lichter et al., 2008). Soil moisture content in no-till systems is often higher than in conventional tillage (Ussiri et al., 2009). Tillage accelerates soil drying and heating/cooling as it disturbs the soil surface and this increases differences in soil temperature (Licht and Al-Kaisi, 2005; Ussiri and Lal, 2009). The soil structure in soil with no-till and residue retention is better, so that precipitation infiltrates more rapidly in soil with less runoff and evaporation (Shaver et al., 2002).

It is well documented that organic matter increases in the topsoil of no-tilled soil, mainly in the 0–5 cm soil layer, compared to conventionally tilled soil when residues are retained (Sainju et al., 2006). No-till favors stable aggregates physically protecting organic matter thereby reducing mineralization rates (Lichter et al., 2008). Tillage and conventional ploughing 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 downwards and mixed in the plough layer (VandenBygaart and Angers, 2006). Therefore, more research is needed to study the effect of tillage practice on C sequestration in the deeper soil layers, especially in the (sub)tropical regions of the world where quantitative information is lacking (Govaerts et al., 2009a,b).

Soil management practices are known to affect emissions of greenhouse gasses (GHG), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which contribute to global warming (Omonode et al., 2007). Emission of CO_2 is often lower in no-till than in conventional till (Sainju et al., 2008; Almaraz et al., 2009) although an increase in no-till has also been reported compared to conventional tillage (Oorts et al., 2007). Tillage can increase emission of N_2O (Baggs et al., 2003; Ussiri et al., 2009), have no effect at all (Jantalia et al., 2008) or decrease emission of N_2O compared to no-till (Robertson et al., 2000; Steinbach and Alvarez, 2006).

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Table 1
Physical and chemical properties of the soil profile at El Batán, Mexico.

Characteristics	Soil layer				
	0–6 cm	6–26 cm	26–64 cm	64–170 cm	170–180 cm
Horizon	Ap1	Ap2	A	2Bw	2BC
Clay ($g\,kg^{-1}$)	409	409	422	290	288
Silt ($g\,kg^{-1}$)	240	240	348	280	441
Sand ($g\,kg^{-1}$)	351	351	230	430	271
Bulk density ($g\,cm^{-3}$)	1.10	1.19	1.31	1.27	1.18
θ_{Sat} (vol%)	48.9	48.9	47.1	ND[a]	ND[a]
$\theta_{33\,kPa}$ (vol%)	37.2	37.2	40.3	31.3	45.9
$\theta_{1500\,kPa}$ (vol%)	15.0	15.0	21.7	18.4	23.6
Pore volume (vol%)	58.5	55.1	50.6	52.2	55.5
pH (H_2O)	5.9	5.9	7.2	7.6	7.6
pH (KCl)	5.4	5.4	6.6	6.9	6.9
Total N ($g\,kg^{-1}$)	1.1	1.1	0.8	0.6	0.7
Organic C ($g\,kg^{-1}$)	14.0	14.0	11.2	7.7	9.5
Electrolytic conductivity ($dS\,m^{-1}$)	0.66	0.66	0.46	0.46	0.55

[a] ND: not determined.

Emission of N_2O is the result of so many interacting processes that it is difficult to predict how no-till will affect it as compared to conventional till. It can be assumed that lower temperatures, better soil structure and less compact soils in no-till than in conventional till will reduce emissions of N_2O, while larger soil organic matter, moisture and mineral N contents will favor emissions of N_2O. Although fertilizer applications are the largest contributors to the emission of N_2O in soil, i.e. 35% as estimated for Canada, the contribution of crop residues is also substantial, i.e. 24% (Rochette et al., 2008). Retaining crop residue will increase emissions of N_2O (Singh et al., 2008) and its effect will depend on type of crop, biochemical quality of the residue, agricultural management, and climatic and soil conditions (Novoa and Tejeda, 2006). 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 (Liebig et al., 2005). Methane is consumed by soil methanotrophes, which are ubiquitous in many soils (McLain and Martens, 2006), and is produced by methanogenic microorganisms in the anaerobic locations of a soil (Chan and Parkin, 2001). Agricultural systems are usually 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 many studies have been published investigating the effect of no-till versus conventional tillage, few have investigated simultaneously the effect of tillage (zero tillage (ZT) versus conventional tillage (CT)) and crop residues management (kept (K) or removed (R)) on emission of CO_2, CH_4 and N_2O, dynamics of mineral N (NH_4^+, NO_2^-, NO_3^-) and the sequestration of C in the 0–60 cm soil layer. The objective of this study was to determine the effect of tillage and residue management on fluxes of CO_2, CH_4 and N_2O, dynamics of mineral N, the global warming potential (GWP) of each system considering the GHG emissions from each system, i.e. fertilizer use, tillage and fluxes of GHG from soil, and the C sequestered in soil.

2. Materials 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 (19.318N; 98.508W), situated in the semi-arid, subtropical highlands of Central Mexico. The slope of the soil at the experimental station <0.3%. The station has a mean annual temperature of 14 °C (calculated over 1990–2001) and an average annual rainfall of 600 mm y^{-1}, with about 520 mm falling between May and October. Short, intense rain showers followed by dry spells typify the rainy season and evapotranspiration exceeds rainfall throughout the year as total amount of yearly potential evapotranspiration is 1900 mm. The growing period at the El Batán experimental station has an average length of 132 d (FAO, 1978).

The soil is classified as a Cumulic Phaeozem 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 (Table 1).

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 m × 22 m. The experimental design consisted of 32 management practices in a randomized complete block with two replications, but only four treatments were considered in this work (Table 2). The different management practices applied included CT versus ZT and crop residues management with the residues retained in the field (K) or removed for fodder (R) with a yearly rotation of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). In the CT treatment, the retained residues were incorporated while they were left on the soil surface in the ZT treatment. In the CT treatments, 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 ZT treatments, weed control during the dry season was done with glyphosphate. Planting of both maize and wheat depended on the onset of summer rains and is usually between June 5 and 15. In the plots included in this study, maize was planted in 2008 on May 30 and wheat in 2009 on June 3.

Standard practices in the study included the use of currently recommended crop cultivars with maize planted at 25 kg seeds ha^{-1} with 75 cm spacing between the rows and wheat planted at 110 kg seed ha^{-1} with 20 cm row spacing. Both crops were fertilized at the rate of 150 kg N ha^{-1} using urea. In ZT with wheat, urea was broadcasted at 1st node, while in CT it was incorporated at the last tillage operation. For maize, the urea was banded in at planting. 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.