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Organic carbon and stable ^{13}C isotope in conservation agriculture and conventional systems

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ABSTRACT

Conservation agriculture might have the potential to increase soil organic C content compared to conventional tillage based systems. The present study quantified soil organic carbon (SOC) and soil C derived from C_3 (wheat) and C_4 (maize) plant species using δ^{13}C stable isotope. Soil with 16 y of continuous application of zero tillage (ZT) or conventional tillage (CT), monoculture (M) or rotation (R) of wheat and maize, and with (+r) and without retention (−r) in the field of crop residues were studied in the central highlands of Mexico. The highest SOC content was found in the 0–5 cm layer under ZTM and ZTR with residues retention. The soil cultivated with maize showed a higher SOC content in the 0–10 cm layer with residue retention than without residue. In the 10–20 cm layer, the highest SOC content was found in the CT treatment with residue retention. The SOC stock expressed as equivalent soil mass was greatest in the 0–20 cm layer of the ZTM (wheat and maize) and ZTR cultivated treatments with residue retention. After 16 y, the highest content of soil δ^{13}C was found in ZTM + r and CTM + r treated soil cultivated with maize; −16.56‰ and −18.08‰ in the 0–5 cm layer, −18.41‰ and −18.02‰ in the 5–10 cm layer and −18.59‰ and −18.72‰ in the 10–20 cm layer respectively. All treatments had a higher percentages of C–C_3 (derived from wheat residues or the earlier forest) than C–C_4 (derived from maize residues). The highest percentages of C–C_4, was found in ZTM + r and CTM + r treated soil cultivated with maize, i.e. 33.0% and 13.0% in 0–5 cm layer, 9.1% and 14.3% in the 5–10 cm layer and 5.0% and 6.8% in 10–20 cm layer, respectively. The gross SOC turnover was lower in soil with residue retention than without residues. It was found that the ZT system with residue retention and rotation with wheat is a practice with a potential to retain organic carbon in soil.

1. Introduction

The characteristics of a soil vary with tillage and management practices applied, which, in turn, determines soil fertility (Carter et al., 1998). Conservation agriculture is defined as any management system that includes the following principles (FAO, 2002; Wall, 2006): first, a serious reduction in soil movement with the ultimate goal to eliminate it completely except for the disturbance caused when sowing; second, the preservation of a permanent or semi-permanent organic cover, i.e. standing crop or a layer of stubble, on the soil and third, the rotation of economically viable crops. Research has shown that soil with zero tillage (ZT) and residue retention is better for water management, prevents soil degradation and improves soil structural properties compared to the conventional tillage (CT) (Kay and Vanden Bygaart, 2002; Shukla et al., 2003; Lichter et al., 2008).

The effect of ZT as such on soil organic carbon (SOC) content, however, is more variable (Govaerts et al., 2009). When comparing the C stock for the tillage systems it is important to take into account that bulk density can be affected. Several authors report higher bulk density values for zero tillage than for conventional tillage in the top-soil (Govaerts et al., 2009). If bulk density increases after conversion from conventional tillage to zero tillage, there will be a relative drop in the soil surface in zero tillage. Thus, if samples are taken to the same depth within the plow layer, more mass of soil will be taken from the zero tillage soil. This could increase the mass of SOC in the zero tillage and could widen the difference between the two systems if there is significant SOC

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beneath the maximum depth of sampling (VandenBygaart and Angers, 2006). Ellert and Bettany (1995) therefore, suggested basing calculations of SOC stocks on an equivalent soil mass rather than on genetic horizons or fixed sampling depths in order to account for differences in bulk density.

Research has shown that soil with zero tillage (ZT) and residue retention has a larger SOC content in surface layer than soil with CT (Bayer et al., 2001; Six et al., 2002; Sisti et al., 2004; Diekow et al., 2005; Jantalia et al., 2007). Allmaras et al. (2004) stated that plowing residues into the soil accelerates the decomposition of SOC as opposed to ZT systems where residues are left on the soil surface to decompose slowly. In the south of Brazil, Bayer et al. (2000) compared the long-term effects of ZT and CT both with different crop rotations (almost all soybean-based). The results showed that ZT had higher C stocks in the 0–17.5 cm and 0–40 cm layer than CT. Another study found that the C stocks after 19 y of continuous soybean–wheat were not significantly different under ZT compared to CT (Freixo et al., 2002). Others authors reported the opposite tendency with the highest SOC content (0–60 cm) found in soil with CT compared to soil with ZT and residue retention (Black and Tanaka, 1997; Blanco-Canqui and Lal, 2008). Angers et al. (1997) and Dolan et al. (2006) did not found a significant difference between ZT and CT.

Crop rotation has a positive effect on soil quality indicators (Karlen et al., 2006) and reduced pest and weed management (Howard, 1996). Karlen et al. (2006) showed that SOC was the most sensitive soil quality indicator. The lowest soil quality values and 20-y average profit were associated with continuous corn, while extended rotations that included at least 3 y of forage crops had the highest soil quality values. Buyanovsky and Wagner (1998) reported that a wheat–maize crop rotation was more effective in retaining C in the soil than a monoculture of maize. The effect of crop rotation on SOC retention can be due to increased C input, because of the intensified production, or due to the changed quality of the residue input (Govaerts et al., 2009).

In Mexico, unsustainable practices, such as deforestation, traditional cultivation techniques with burning or removal of crop residues, intensive cattle raising and changes in land use, have accelerated decline in SOC and soil degradation. As a result, 47% of the soils are now considered degraded (SEMARNAT, 2002). Declining SOC contents in agro-ecosystems are relevant for the global C budget as less C is sequestered in the soil. This decline in SOC has encouraged the development of SOC conservation practices (Huggins et al., 1998; Fischer et al., 2002). Therefore in 1991, an experiment was set up at the México based highland research station of the International Maize and Wheat Improvement Centre (CIMMYT), to investigate the effect of different management practices, i.e. ZT or CT with and without residues retention and maize–wheat rotation or monoculture, on soil degradation and yields (Govaerts et al., 2006, 2007).

The determination of δ^{13}C in soil helps to understand the dynamics of SOC and its origin, being it from C_3 or C_4 plants, so that techniques can be evaluated and decisions be made on the implementation of practices that maintain or increase SOC (Stemmer et al., 1999; Lobea et al., 2005). Balesdent et al. (1990), for instance, used δ^{13}C measurements to demonstrate that the rate of decomposition of SOC increased after tillage. The technique has also often been used to study dynamics of SOC in tropical agro-forestry systems (Diels et al., 2001, 2004; Ellert and Janzen, 2006; Oelbermann et al., 2006), but not often in temperate or semi-arid regions (Oelbermann and Voroney, 2007).

Tillage, management of residues and crop rotation influence the SOC stocks and CO_2 emissions in agriculture practices: (West and Post, 2002; Allmaras et al., 2004). Conservation agriculture could be an alternative to enhance C sequestration compared to conventional systems, but results vary from study to study. This paper hypothesized that the application of conservation agriculture is an alternative for C sequestration in the semi-arid regions subtropical highlands of Central Mexico. We (i) investigated the effect of 16 y of ZT compared to CT, crop rotation (monoculture and rotation), crop residue management (with and without residues) and their interactions on SOC content (% and stock), (ii) determined the proportion of C in soil derived from C_3 and C_4 plants using δ^{13}C measurements and (iii) calculated the gross SOC turnover in the different agricultural systems.

2. Materials and methods

2.1. Experimental site

The study was conducted at the El Batán Experimental Station of CIMMYT, situated in the semi-arid, subtropical highlands of Central Mexico (19° 31′ North, 98° 50′ West, 2259 masl), in a Cumulic Phaeozem (WRB, 2006) or fine, mixed, thermic Cumulic Halplustoll (Soil Survey Staff, 2003) and the granolumetric distribution is: sand (1000–50 μm) 25%, silt (50–2 μm) 37% and clay (<2 μm) 38%. The initial conditions of the top-soil (0–20 cm) in 1991, are given in Table 1. The station has a mean annual temperature of 14 °C and an average annual rainfall of 600 mm per year, 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 (total amount of yearly potential evapotranspiration is 1900 mm) (Govaerts et al., 2005).

The experiment was set up in 1991 in an area of 1.3 ha, where 64 plots of 7.5 × 22 m each were laid out. Slope was 0.3% (north–west). Thirty-two treatments were applied in a randomized complete block design with two replicates. Sixteen treatments are included in this study, each consisting of combinations of ZT (zero tillage) and CT (conventional tillage) with crop residues retention (+r) and without crop residues retention (−r). The four combinations resulting from these treatments were sown as monoculture (M) of maize (*Zea mays L.*) or wheat (*Triticum aestivum L.*) and with maize in rotation with wheat or wheat with maize. Each phase of the rotation was present each year (R).

The soil preparation in CT consisted of harrowing at 20 cm depth, with a disc harrow starting some days after harvest incorporating the crop residue where residue is kept in the field, and repeated when needed for weed control (at least once) during the dry season. To prepare the seed bed a spike tooth harrow was used once. The ZT plots were sown directly with maize or wheat using an Almaco® seeder and Aitcheson® machine respectively, both using disc openers for seed placement. The sowing period was in May and harvest period in October for wheat and November for maize. In the treatments with residue retention (+r) all the residues of the former crop were kept in the field; in CT plots the residues were ploughed into the ground and in ZT they were left on the soil surface. In the treatments where the residues were removed (−r),

Table 1
Initial conditions in 1991 of the top-soil (0–20 cm) of CIMMYT's long-term tillage sustainability trial, El Batán, México.

Parameter	Value	Parameter	Value
Total-N	1.3 g kg^{-1}	CEC	22.15 cmolc kg^{-1}
Organic carbon	17.3 g kg^{-1}	BS	90%
Olsen-P	0.81 mg kg^{-1}	pH(1:2) H_2O	6.48
K	1.18 cmol kg^{-1}	EC	0.13 dS cm^{-1}
Ca	7.15 cmol kg^{-1}		
Mg	3.1 cmol kg^{-1}	FC	34%
Na	0.47 cmol kg^{-1}	PWP	18%

CEC = Cation Exchange Capacity; BS = Base saturation; EC = Electrolytic conductivity; PWP = Permanent Wilting Point; FC = Field Capacity; All data were expressed on dry soil basis.