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Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality

Mariela Fuentes[a], Bram Govaerts[b,*], Fernando De León[c], Claudia Hidalgo[a], Luc Dendooven[d], Ken D. Sayre[b], Jorge Etchevers[a]

[a] Colegio de Postgraduados, Laboratorio de Fertilidad, IRENAT Km 36.5 Carretera México-Texcoco, Montecillo, México, CP 56230, Mexico
[b] International Maize and Wheat Improvement Centre (CIMMYT), Apdo. Postal 6-641, 06600 Mexico, D.F., Mexico
[c] Universidad Autónoma Metropolitana-Xochimilco, Laboratorio de Fisiología y Tecnología de Cultivos, Calzada del Hueso 1100, Col. Villa Quietud, 04960 México, D.F., Mexico
[d] Cinvestav, Dept. Biotechnology and Bioengineering, Av. Instituto Politécnico Nacional 2508, C.P. 07360, México, D.F., Mexico

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ABSTRACT

Soil management systems may negatively affect the quality of the soil. Policymakers and farmers need scientific information to make appropriate land management decisions. Conventional (CT) and zero tillage (ZT) are two common soil management systems. Comparative field studies under controlled conditions are required to determine the impact of these systems on soil quality and yields. The research presented studied plant and soil physical and chemical characteristics as affected by different agricultural management practices, i.e. ZT and CT, cropped with continuous wheat or maize in monoculture (M) or in a yearly rotation (R) of these two crops, either with residue retention (+r) or without residues retention (−r), in an experimental field in the Transvolcanic Belt of Mexico after 14 years. The dominant factors defining soil quality were organic C, total N, moisture, aggregate stability, mechanical resistance, pH and EC. The principal component combining the variables organic C, total N, aggregate stability and moisture content showed the highest correlations with final yield (R = 0.85 for wheat and 0.87 for maize).

After 14 years of continuous practice, ZTM + r and ZTR + r had the best soil quality and produced the highest wheat and maize yields of average 2001–2004 (6683 and 7672 kg ha^{-1} and 5085 and 5667 kg ha^{-1}, respectively). Removing the residues, i.e. treatments ZTM − r with maize (average 2001–2004: 1388 kg ha^{-1}) and ZTR − r and CTR − r with wheat (average 2001–2004: 3949 and 5121 kg ha^{-1}), gave the lowest yields and less favourable soil physical and chemical characteristics compared to the other practices. It was found that zero tillage with residue retention is a feasible management technology for farmers producing maize and wheat in the agro-ecological zone studied, resulting in a better soil quality and higher yields than with the conventional farmer practice (maize monoculture, conventional tillage and residue removal).

1. Introduction

Soil quality has been defined as 'the capacity of a soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation' (Karlen et al., 1997) or 'fitness for use' (Larson and Pierce, 1994; Tugel et al., 2005). Soil quality depends on the extent to which a soil fulfils the role it is used for (Singer and Ewing, 2000). Therefore, within the framework of agricultural production, high soil quality equates to high productivity without significant soil or environmental degradation. Soil quality describes the status or specific condition of the soil as a result of its management (Karlen et al., 2003). Evaluation of soil quality is based on physical, chemical and biological characteristics of the soil, which vary as a function of the management applied, such as tillage, crop rotation, and the handling of crop residues. It is well known that soil characteristics vary in relation to the type of tillage and the techniques applied, which determines the degree of degradation of the soil and its capacity to sustain crop production (Carter, 1994). Changes in soil quality are not only associated with management, but also with the environmental context, such as temperature and precipitation (Andrews et al., 2004).

Larson and Pierce (1994) referred to the difficulty of properly estimating soil properties and soil quality. Therefore, they proposed

* Corresponding author. Tel.: +52 55 5804 2004; fax: +52 55 5804 7558.
E-mail address: b.govaerts@cgiar.org (B. Govaerts).

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the use of a minimum set of quantitative data (MDS) regarding the chemical, physical and biological characteristics of soil that were easy to measure. As such, factors that control changes in soil quality can be investigated and changes over time can be explained.

Over the past years, various agronomic management systems have been proposed and tested that preserve or improve soil quality. One of these systems is conservation agriculture. Conservation agriculture is defined as any management system that includes the following characteristics (Wall, 2006): first, a serious reduction in soil movement with the ultimate goal to eliminate it completely except for the disturbance caused when sowing, i.e. zero tillage (ZT); 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. Conservation agriculture based technologies reduce water and wind erosion by approximately 50%, in contrast to conventional tillage (CT) (Figueroa and Morales, 1992). In the past, CT was based on the use of human and animal force and manure. Since the second half of the 20th century, it has resorted mostly to the use of agricultural machinery and chemicals to achieve yield increase. Although CT resulted in yield increments, yet soils subjected to CT for a long time can be negatively affected in terms of their physical, chemical and biological conditions, with the consequence that they cannot sustain their historical level of production. Consequently, larger amounts of fertilizers are applied with use of more machinery to simply maintain yields as the production system is no longer sustainable and the soil quality is reduced (Lampkin, 1998).

Water is the primary constraint to crop production in semi-arid regions. Approximately 40% (600 Mha) of the world's cropland area is affected by low and unpredictable rainfall, with 60% of these lands located in developing countries (Johnston et al., 2002). Zero tillage combined with crop residue retention on the soil surface, can improve moisture infiltration, and greatly reduce erosion and enhance water use efficiency compared to CT (Johnston et al., 2002; Shaver et al., 2002). Crop residue on the soil surface forms a barrier to water loss by evaporation, increasing the amount of moisture stored in the plant root zone and available to the crop. Field research has shown higher moisture levels, decreased soil temperatures and also more stable soil aggregates, i.e. improved soil structure, under ZT compared to CT (Carter, 1992; Lichter et al., 2008).

In Mexico unsuitable practices such as deforestation, traditional crop production, intensive cattle raising and changes in land use have propitiated increases in soil degradation, to such an extent that currently 47% of the soils are degraded (SEMARNAT, 2002). This has generated and worsened problems related to soil fertility in its different physical, chemical and biological aspects. In the Mexican semi-arid highlands, there is currently a predominance of continuous maize monoculture and mechanical tillage. Maize stover is often removed from the field for animal feed. Cereal grain yields are <3 t ha^{-1}, fields are often weedy and nitrogen deficient, soil structure is poor, and sheet and gully erosion is widespread (Fischer et al., 2002; Govaerts et al., 2008). Therefore, in 1991, at the International Maize and Wheat Improvement Centre (CIMMYT) in Mexico, an experiment was set up investigating different agronomic managements (ZT and CT with and without residues, monoculture and maize–wheat rotation) to look at the potential of the above presented conservation agriculture based technologies to reverse and ameliorate the problems in the target area. One year after the start of the experiment (1992), N mineralization rate in ZT with residue were higher than CT with and without residue (Etchevers et al., 2000) and at 2 years microbial biomass was found to have increased in ZT and CT with residue as compared to ZT and CT without residue (Fischer et al., 2002; Vidal et al., 1998), a trend that was confirmed in 1994 and 1996, for the C associated with biomass (Etchevers et al., 2000). After more than 10 years several of the effects of long-term tillage, residue management, and crop rotation became clear. The ZT with residue retention and crop rotation resulted in high and stable yields, increased soil micro-flora catabolic capacity as well as soil microbial biomass, while parasitic nematodes decreased as compared to conventional tillage and zero tillage without residue (Govaerts et al., 2005, 2006, 2007a).

The objective of the present research was (i) to determine the effect on physical and chemical soil quality following 14 years of continuous application of ZT as compared to CT, crop rotation (monoculture and rotation) and crop residue management (with and without residues), (ii) to evaluate the potential of conservation agriculture based technologies as opposed to the traditional farmer practice and (iii) to determine the relationship between the soil quality and the crop yields.

2. Materials and methods

2.1. Field experiment

The study was conducted at the El Batán Experimental Station of CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo), situated in the semi-arid, subtropical highlands of Central Mexico (19°31′ North, 98°50′ West, 2259 m a.s.l.), in a Cumulic Phaeozem soil (IUSS, 2006) or fine, mixed, thermic Cumulic Halplustoll (Soil Survey Staff, 1998) and the granulometric distribution is as follows: sand (1000–50 μm) 25%, silt (50–2 μm) 37% and clay (<2 μm) 38%. The station has a mean annual temperature of 14 °C and 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 32 plots of 7.5 m × 22 m each were laid out. Slope was 0.3% (north to west). Sixteen treatments were carried out with two replicates each consisting of combinations of ZT (zero tillage) and CT (conventional tillage) with residues (+r) and without residues (−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 (R) with wheat or wheat with maize. Each phase of the rotation was present each year. The experimental design was a randomized complete block.

The soil preparation in CT consisted of the following operations for maize and wheat: 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. The number of emerging plants was 6.5 plants m^{-2} for maize and 293 plants m^{-2} for wheat. 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 surface. In the −r treatments, that is where the residues were removed, most of the aerial residues were removed simulating the farmers practice. Both crops were fertilized at the rate of 120 kg N ha^{-1} using urea, with all N applied to wheat at the first node growth stage (broadcast) and to maize at the 5–6 leaf stage (surface-banded).

2.2. Soil sampling and analyses

Soil was sampled after harvest of maize and wheat, i.e. December, in 2003 and before planting, i.e. May, in 2004 both samples