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Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term experiment in Switzerland

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ABSTRACT

To address the influence of soil tillage reduction on crop yield and soil properties, an experiment was set up in 1969 in the western part of Switzerland. A conventional tillage treatment with plough was compared to a minimum tillage treatment and a deep non inversion tillage treatment, converted to no till in 2007. Evolution of crop yield through time was investigated, as well as the soil properties in 2013. Mean soil properties and their stratification with depth were assessed. The results showed that, after 44 years, globally, all tillage treatments allowed to maintain similar yields in the long term. However, during the same time, soil properties have changed deeply. Soil organic carbon has decreased compared to the initial situation, in all treatments except in the minimum tillage. This treatment also allowed to reach high clay to carbon ratio in the upper layer, suggesting good soil structural quality compared to the other treatments. In contrast, this did not result in significant differences in carbon stocks between tillage treatments, probably due to low carbon inputs in all treatments. In addition, a strong stratification pattern with depth was observed for most of the nutrients in the minimum tillage treatment, while the situation was more homogeneous in the plough treatment. The adoption of no till also modified soil properties and lead to clear stratification patterns after only six years. These results showed that crop yield could globally be maintained in reduced tillage systems, while insuring high soil fertility and structural quality. The important decrease in the number of tillage interventions and intensity of disturbance induced an improvement of soil properties. Reduced tillage practices could thus be advantageously adopted to insure crop production together with soil fertility improvement in rather short time period.

1. Introduction

Since its beginning, agriculture has been, and still is, a major driver of soil degradation worldwide (Virto et al., 2015). Major issues related to soil in agricultural systems are erosion, run-off, nutrient leaching and soil fertility loss (Tilman et al., 2002). To respond to these problems, and lower labour and fuel costs, reduced tillage has been increasingly adopted, first in America and then in Europe (Derpsch et al., 2014; Hobbs et al., 2008; Holland, 2004; Palm et al., 2014; Soane et al., 2012). The reduction of soil tillage can be more or less drastic, going from non inversion deep tillage to more extreme techniques such as shallow tillage, strip till or direct seeding. Reduced tillage has many beneficial effects, either directly or indirectly through the increase in surface residue often linked to this practice. It generally allows preserving soil fertility and biological activity, decreasing machine induced compaction, and reducing erosion and run-off (Holland 2004; Soane et al., 2012; Murugan et al., 2014; Palm et al., 2014). However, weed control is often more difficult in reduced tillage systems, and these systems widely rely on an increasing use of herbicide (Melander et al., 2013). Beneficial and detrimental effects of tillage reduction have thus to be balanced to improve the overall sustainability of the system.

Similar crop yield can be usually achieved in conventional ploughed and reduced tillage systems, though an initial transient decrease is often observed in no till systems. For example, Pittelkow et al. (2015a, 2015b) have shown that yield of most crops is reduced in no till systems with less than 5 years of practice compared to conventional systems, but is then equal. Varying changes of soil properties are expected with the abandonment of plough (Mazzoncini et al., 2011; Rasmussen, 1999; Soane et al., 2012). A most controversial issue is the ability of untilled soils to stock organic carbon (Dimassi et al., 2014). While it has been long postulated that the reduction of tillage could allow to stock carbon in soils, it has been increasingly shown that differences in soil carbon

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stocks between differently tilled systems is mainly linked to the amount of carbon inputs (mainly crop residues) to the soil (Autret et al., 2016; Virto et al., 2012) and to the method and depth of calculation of stocks (Dimassi et al., 2013; Ellert and Bettany, 1995) rather than to the intensity of tillage.

In any cases, all modifications induced by the reduction of tillage must be assessed on the long term, as many soil properties are changing slowly. In addition, several years are generally needed for the system to equilibrate after major changes such as plough abandonment. Long term experiments are thus best suited to study the effect of reduced tillage on soil properties. Several long term experiments on soil tillage exist in Europe, for example in the United Kingdom, France, Italy, Sweden. In the western part of Switzerland, an experiment comparing four modalities of tillage was set up by Agroscope in 1969. It included a conventional plough treatment and three reduced tillage treatments (deep non inversion tillage, shallow non inversion tillage and minimum tillage). In 2007, the deep non inversion tillage treatment was converted to no till. The objectives of this study were to investigate the effect of reduced soil tillage on (i) crop yield and its stability and (ii) the evolution of soil characteristics, and (iii) to study the effect of short term transition from deep tillage to no till on the same properties.

2. Materials and methods

2.1. Experimental site and design

The experiment was established in 1969 by Agroscope in Changins (46°24′ N, 06°14′ E, 430 m above sea level), Switzerland. The average total annual precipitation is 999 mm and the mean temperature 10.2 °C (30-year averages, 1981–2010). The soil of the experimental field is a Cambisol, divided into two parts presenting different textures, a clay (48% clay-37% silt) and a loam (25% clay-44% silt) soil.

The experiment follows a randomized complete block design with four main treatments of soil tillage. Until 2007, the following treatments were compared: (i) deep inversion tillage (conventional tillage with plough) 'PL', 20–30 cm, (ii) deep non inversion tillage 'DN', 25–30 cm, (iii) shallow non inversion tillage, 10–15 cm, (iv) minimum tillage 'MT', 5–10 cm. In 2007, the deep non inversion tillage treatment ('DN') was converted into a no till treatment 'NT' (last tillage in autumn 2006). As the third treatment was not monitored during the last soil analyses campaign, it was not included in this study. Each treatment is replicated three times on the clay soil and four times on the loam soil. The unit plot has a surface of 148 m^2.

2.2. Cultivation and fertilisation practices

The crop rotation, winter wheat (*Triticum aestivum*) − winter rapeseed (*Brassica napus*) − winter wheat − grain maize (*Zea mays*), is typical for the region. In 1993 and 2001, bad weather conditions in autumn prevented the seeding of winter wheat, which was replaced by spring wheat. Crop variety, sowing date, fertilisation (according to Swiss fertilisation guidelines, Sinaj et al., 2009), as well as fungicide and insecticide management (according to integrated crop protection principles; Häni et al., 1990) are identical for all treatments. By contrast, the timing of soil tillage and weed management are specific to each treatment. The same varieties were used for as long as possible over time. When a change was required, new varieties with similar precocity and varietal characteristics were selected. For winter wheat, only two different varieties (high quality for bread making varieties) have been used throughout the experiment, while nine varieties of winter rapeseed and eight varieties of grain maize have been sown (Supplementary Table S1).

Until 2007, wheat straw used to be exported, while maize and rapeseed residues were chopped and left on the field. Since 2007, residues of all crops are left on the field. Cover crops were sown before grain maize in 2000 (white mustard), 2008 (indian mustard) and 2012 (clover-mustard mixture), in all treatments.

Currently, the main tillage implements used for the different treatments are a mouldboard plough (PL), and a rototiller (MT). The no till treatment (NT) involves a direct seeder developed for experimentation purposes. A chisel plough was used in the deep non inversion tillage treatment (DN).

2.3. Data collection and soil analyses

Machine harvest was applied throughout the experiment to determine grain yield for each year in each treatment, from 1969 to 2013. Grain weight and humidity are measured at harvest and then used to compute dry grain yield in t/ha.

Soil organic carbon content was analysed sporadically since the beginning of the experiment, for the layer 0–20 cm, resulting in a series of 15 time points, including the initial state in 1969.

In 2013, a full campaign of soil analyses was conducted on all treatments except the shallow non inversion tillage. Soil samples, at least eight cores with a diameter of 3 cm, were taken from three soil layers (0–5, 5–20 and 20–50 cm) after wheat harvest, in August 2013. Plant residues were removed from the soil samples and the individual samples were mixed to form a composite sample for each plot. Samples were oven-dried at 55 °C during 72 h, sieved at 2 mm and analysed for the following soil properties: pH-water (pH-H_2O), cation exchange capacity (CEC), soil organic carbon (SOC), total nitrogen (N_{tot}), total (P_{tot}) and organic phosphorus (P_{org}), total potassium (K_{tot}), total magnesium (Mg_{tot}), total manganese (Mn_{tot}), total zinc (Zn_{tot}), total copper (Cu_{tot}), total iron (Fe_{tot}) and available forms (P_{NaHCO3}, K_{AA}, Mg_{AA}, Mn_{DTPA}, Zn_{DTPA}, Cu_{DTPA}, Fe_{DTPA}). All these elements were measured according to the Swiss standard methods (Agroscope, 1996), except P_{org} (Saunders and Williams, 1955) and P_{NaHCO3} (Olsen et al., 1954). Potential cation exchange capacity was measured according to Metson (1956). The carbon to nitrogen ratio C/N was obtained by dividing SOC by N_{tot}.

Bulk density was determined in one soil pit for each plot, at four different depths: 0–6 cm, 5–11 cm, 14–20 cm and 32–38 cm. Steel cylinders (radius: 5 cm, height: 6 cm, volume: 471 cm^3) were used to take intact soil cores, which were then dried for 72 h at 105 °C and weighted. Humidity at sampling was about 30% for the clay soil and 19% for the loam soil. Bulk density results from the 5–11 cm and 14–20 cm cylinders were averaged to represent the value of the 5–20 cm layer. The 0–6 cm and 32–38 cm cylinders were used to represent, respectively, the 0–5 cm and 20–50 cm layers.

2.4. Data analysis

To characterise each treatment, the number of tillage interventions was computed for each cultural year (from the harvest of the preceding crop to the harvest of the main crop) over the whole period from 1969 to 2013. As harvest and seeding operations are each year the same for all treatments they were not taken into account. In addition, the intensity of tillage operations was evaluated using the 'Soil Tillage Intensity Rating STIR' method from the RUSLE2 framework (USDA NRCS, 2012). This method attributes a value to each tillage implement, reflecting the intensity of soil perturbation. These values are then summed over the year to obtain a total STIR value for the cultural year.

The effect of tillage treatments on crop yield was tested by an analysis of variance, first for all crops and soils together, and then separately for each crop (n = 3) x soil (n = 2) combination. The effect of tillage on mean rotation yield (from the first one 1969–1972 to the eleventh 2010–2013) was also assessed using analyses of variance, for both soil together. For each crop in each treatment, yield stability was assessed by computing the coefficient of variation of yield on all years as well as the mean rank of yield for each treatment (1 = lowest yield, 3 = highest yield).

The evolution of soil organic carbon (0–20 cm) through time was tested using a Mann-Kendall trend test (R package 'Kendall', McLeod,