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Improvement of soil structure through organic crop management, conservation tillage and grass-clover ley

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ABSTRACT

Conventional intensive tillage is a widespread soil management practice that controls weeds and promotes nutrient mineralization at the expense of a degraded soil structure and soil carbon (C) loss. Alternative soil management practices such as no tillage, reduced tillage and temporary leys, however, can minimize the negative effects of intensive tillage on soil structure. To improve understanding of these management practices on soil structure, we sampled a field trial combining organic and conventional crop management with different intensity levels of tillage, resulting in four cropping systems: conventional intensive tillage (C-IT), conventional no tillage (C-NT), organic intensive tillage (O-IT) and organic reduced tillage (O-RT). A ley period was added following a 4-year arable crop rotation. We measured mean weight diameter (MWD), total C and total nitrogen (N) in whole unfractionated soil and water-stable aggregate fractions after the 4-year arable crop rotation and again after a following 2-year grass-clover ley period, to assess the impact of the cropping system and the ley, respectively. Results showed that 4 years of organic crop management including the application of cattle manure slurry combined with reduced tillage led to significantly better soil structure (i.e. aggregate MWD) at the 0–6 cm soil depth, compared to the other cropping systems tested. After the ley period, the proportion of large macroaggregates increased by 65% for C-IT and 47% for O-IT at 0–6 cm depth. Total C increased significantly for only O-IT and O-RT after the ley, both of which also showed a high C stratification between 0–6 cm and 6-20 cm depth. In conclusion, soil structure is most improved during continuous cropping when combining organic crop management with reduced tillage, while a ley period was effective in improving the soil structure in intensive tillage plots to the level of O-RT.

1. Introduction

The impacts of tillage and crop management type extend well beyond crop productivity; they influence soil microbial activity (Lori et al., 2017), greenhouse gas emissions (Stavi and Lal, 2013), soil structure and C sequestration (Gattinger et al., 2012; Guo and Gifford, 2002). The widespread and long-term use of intensive tillage has led to significant soil degradation under a number of soil types, including soil compaction and soil erosion, with a concomitant loss of soil organic carbon (SOC).

Sustainable agricultural intensification and ecological intensification are examples of different initiatives which aim to reconcile agricultural productivity with long-term environmental sustainability (Bommarco et al., 2013; Govers et al., 2017). Both initiatives advocate for supporting soil functionality and improving nutrient recycling. Practices that allow for this include conservation tillage, organic crop management and the use of leys.

Conservation tillage spans tillage variations that leave at least 30% of crop residue on the surface (Soil Science Society of America, 2008). These types of conservation tillage including no tillage, reduced, ridge, chisel, disk, sweep tillage, alone or combined, have shown to be effective in reducing soil erosion (Lynch, 2012). No tillage covers about 4% and 25% of arable land in the EU and USA, respectively (EUROSTAT, 2013; U. S. Department of Agriculture, 2014), while other forms of conservation tillage are practiced in almost 20% of arable land in the EU and 27% in the U.S. Organic crop management has been shown to

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benefit biodiversity and increase soil organic matter (SOM) content in comparison with conventional crop management (Gomiero et al., 2011). One drawback, however, is that it usually relies on intensive tillage for mechanical weed control since synthetic herbicides are not permitted. Leys are temporary grasses or grass-forb mixtures grown during arable crop rotations that can serve to facilitate weed control and produce forage.

Soil structure affects the movement of water, solutes, microorganisms, gases and plant roots, which influence soil functions (Bronick and Lal, 2005; Carter, 2002; Nicolodi and Gianello, 2014). Soil aggregation is often used as a measure for soil structure (Six et al., 2000) despite ongoing difficulties in defining critical limits (Carter, 2002). The formation of aggregates, i.e., water-stable soil size classes with intrinsic varying physical and chemical characteristics (Elliott, 1986), leads to the physical protection of C from mineralization by microorganisms (Balesdent et al., 2000; Schimel and Schaeffer, 2012). During the formation of aggregates, inter-aggregate organic matter is incorporated (Six et al., 2004a). Considering that physical access to occluded substrates is a limiting factor for organic matter breakdown in mineral soils (Schimel and Schaeffer, 2012; Tisdall and Oades, 1982) this incorporation of organic matter into aggregates can contribute to longer-term soil C sequestration (Kong et al., 2005). Aggregate stability is often lower under intensive tillage (Elliott, 1986; Kravchenko et al., 2011), encouraging a loss of C-rich macroaggregates (> 250 μm) while increasing C-poor microaggregates (250–53 μm) (Six et al., 2000). Increasing SOM is sought, since it improves soil quality through altering nutrient availability, water holding capacity, soil porosity, cation exchange capacity and soil aggregation (Bronick and Lal, 2005; Kaiser et al., 2008; Mangrich et al., 2015). Given the advantages of good soil structure in supporting soil processes, practices that foster aggregate stability should be encouraged.

In this study, we used a field experiment to quantify the effect of four different cropping systems resulting of the combination of organic or conventional crop management with different levels of tillage, i.e. conventional intensive tillage, conventional no tillage, organic intensive tillage and organic reduced tillage, as well as a ley period on soil aggregate stability and aggregate-associated C and N storage. Measurements were taken after a 4-year arable crop rotation to evaluate the effects of the different cropping systems, and repeated following a 2-year grass-clover ley period to assess the effect of ley. We hypothesized that reduced tillage and no tillage would improve soil structure by reducing soil physical disturbance in comparison with intensive tillage, resulting in a higher mean weight diameter and total carbon (TC) content in comparison to intensive tillage. Similarly, we hypothesized that organic crop management would improve soil structure compared to conventional crop management due to the additional C input from the cattle slurry fertilizer. Finally, we hypothesized that the minimal physical disruption and particle binding action of plant roots and their exudates during the ley period would result in an increase in C content and improvement in soil structure across all cropping systems.

2. Methods

2.1. Field site and experimental design

The Swiss Farming System and Tillage experiment (FAST), described in detail by Wittwer et al. (2017), compares conventional and organic crop management with different tillage intensities in 6-year rotations. The field experiment is located at the Swiss federal research station Agroscope, Reckenholz near Zurich, Switzerland (47°26′20″N, 8°31′40″E). The soil is a Cambisol on glacially deposited Pleistocene sediments containing 23% clay, 34% silt and 43% sand (IUSS Working Group, WRB, 2014). Mean annual temperature is 9.4 °C (Swissmeteo), while annual precipitation averages 1054 mm (1981–2010 data).

The crops rotating in the first 4 years are representative of local Swiss farming practices. The rotation started with winter wheat (*Triticum aestivum* L. cv. Titlis), followed by maize (*Zea mays* cv. Padrino), field bean (*Phaseolus vulgaris* cv. Fuego) and winter wheat (*Triticum aestivum* L. cv. Titlis). Finally, a grass-clover mixture (UFA 330) was sowed for a 2-year period. The experiment started in August 2009 and was set-up as a randomized complete block design replicated four times, where each plot measured 6 m × 30 m.

The management practices tested are crop management (i.e., conventional and organic) and tillage type (i.e., intensive tillage, reduced tillage and no tillage). The combination of both factors resulted in four cropping systems: conventional intensive tillage (C-IT), conventional no tillage (C-NT), organic intensive tillage (O-IT), and organic reduced tillage (O-RT). Intensive tillage was applied to 0.2 m depth using a moldboard plow (Menzi B. Schnyder, Brutten, Switzerland) followed by a rotary harrow at 0.05 m depth (Amazone, H. Dreyer GmbH, Germany) for both conventional and organic crop management. Conservation tillage consisted of no tillage and direct seeding under conventional crop management, whereas reduced tillage was applied under organic crop management, with a superficial tillage at 0.05 m depth using a disk harrow in the first year and a rotary harrow thereafter.

Both O-IT and O-RT were fertilized with cattle manure slurry whereof on the average 40% of the total N content was in the form of NH_4-N, and the rest organic N. This was distributed among the wheat crops (107 kg N ha^{-1} yr^{-1} in two applications), maize (137 kg N ha^{-1} yr^{-1} in two applications), and the grass-clover ley (205 kg N ha^{-1} $year^{-1}$ in four applications). Fertilization in C-IT and C-NT consisted of ammonium-nitrate applications with an input of 110 kg N ha^{-1} yr^{-1} for the wheat crops, 90 kg N ha^{-1} yr^{-1} for maize, and for the grass-clover ley 130 kg N ha^{-1} the first year and 100 kg N ha^{-1} the second year. The grass-clover was harvested five times the first year and four times the second year, with fertilizer applied in equal splits after each cut.

2.2. Soil sampling

Soil was sampled at the end of the fourth growing season (August 2013, after wheat harvest), as well as immediately following two years of grass-clover ley (August 2015). Four intact soil cores (5.5 cm × 20 cm) were taken at 3 m intervals from the center of each replicate plot using a Giddings hand sampler (Giddings Machinery Co, Windsor, Colorado, USA). Each 20 cm-length core was manually cut at 6 cm, separating the top 0–6 cm from the bottom 6-20 cm. Field-moist cores were sieved at 8 mm by manually crumbling along natural fracture lines in order to minimize aggregate disruption. The four cores from each plot were combined and each composite sample was air-dried and stored at room temperature.

2.3. Physical fractionation of soil aggregates

Air-dried soil was wet-sieved following Elliott (1986) to separate four aggregate size classes: large macroaggregates (LM; > 2000 μm), small macroaggregates (SM; 2000–250 μm), microaggregates (mi; 250–53 μm) and silt and clay (S + C; < 53 μm). To accomplish this, eighty grams of air-dried soil was distributed evenly on a 2000 μm sieve and for 5 min submerged in deionized water for slaking. Then, the sieve was manually raised and lowered rhythmically 50 times over the course of two minutes taking care to maintain an even force throughout the process (Elliott, 1986). The water-stable aggregates on the sieve (i.e. macroaggregates) were backwashed into a tin and oven dried at 60 °C. The remaining soil-water mix was poured over the next smaller sieve and the procedure was repeated with the 250 μm and 53 μm sieves to isolate the remaining size classes. Mean weight diameter (MWD), used as a measure of soil structure, was calculated using the proportional abundance of each aggregate fraction and the mean diameter of each size class as defined in Eq. (1).