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Responses of soil properties and crop yields to different inorganic and organic amendments in a Swiss conventional farming system

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ABSTRACT

In agro-ecosystems, fertilization practices are crucial for sustaining crop productivity. Here, based on a 50-year long-term experiment, we studied the influence of fertilization practices (inorganic and/or organic) and nitrogen (N) application rates on (i) soil physicochemical properties, (ii) microbial and earthworm communities and (iii) crop production. Our results showed that soil organic carbon content was increased by incorporation of crop residues (+2.45%) and farmyard manure application (+6.40%) in comparison to the use of mineral fertilizer alone. In contrast, soil carbon stock was not significantly affected by these fertilization practices. Overall, only farmyard manure application improved soil physicochemical properties compared to mineral fertilization alone. Soil microbial population was enhanced by the application of organic amendments as indicated by microbial biomass and phospholipid-derived fatty acids contents. The fertilization practices and the N application rates affected significantly both the biomass and composition of earthworm populations, especially the epigeic and endogeic species. Finally, farmyard manure application significantly increased crop yield (+3.5%) in comparison to mineral fertilization alone. Crop residue incorporation rendered variable but similar crop yields over the 50-year period. The results of this long-term experiment indicate that the use of organic amendments not only reduces the need for higher amount of mineral N fertilizer but also improves the soil biological properties with direct effects on crop yield.

1. Introduction

In agro-ecosystems, fertilization practices influence soil quality and crop productivity. Depending on the nature of the applied fertilizer (organic or inorganic), modifications of soil properties have been observed over the long-term under different pedoclimatic conditions (Rasmussen et al., 1998). The specialization of farming activities has led to the spatial segregation of crop and livestock productions, thus causing a drastic decrease in the use of animal manure as organic amendment in many conventional farms in Switzerland (Vullioud et al., 2004) and more generally in western Europe (Chesworth, 2008). As a result, the necessity for maintaining soil organic carbon (SOC) at sufficient levels in arable fields has become an important issue.

Soil organic carbon is a crucial parameter for soil fertility as it enhances soil physical, chemical and biological properties (Birkhofer et al., 2008; Lützow et al., 2006). Indeed, an increase of SOC content may promote crop yields through increased nutrient supply (Haynes and Naidu, 1998; Maltas et al., 2013) and improved water retention capacity (Edmeades, 2003). Furthermore, SOC contributes to the attenuation of environmental impacts of farming activities so that, for example, soil erosion is reduced (Six et al., 2002) and nutrient leaching is minimized (Drinkwater et al., 1998). Soil organic matter (SOM) is also the most important terrestrial pool for carbon (C) sequestration (Lal, 2002), and its management is therefore relevant for the mitigation of climate change (Lal, 2004).

The dynamic of soil organic carbon (SOC) is directly related to the amount of C supplied to the soil and the rate of SOM decomposition (Lal, 2002). In agro-ecosystems, fertilization practices influence SOC content by modifying both C inputs and

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losses (Follett, 2001). In general, the application of organic amendments such as crop residues and/or farmyard manure increases significantly SOC (Diacono and Montemurro, 2010; Lützow et al., 2006; Maltas et al., 2013), whereas the long-term application of only inorganic fertilizers often has the opposite effect (Edmeades, 2003). The decomposition rate of SOM is influenced by many factors such as (i) the chemical composition and the molecular structure of organic matter (OM) (Kögel-Knabner, 2002); (ii) the physical protection of OM within soil aggregates (Six et al., 2002) and/or (iii) the soil biological activity (Condron et al., 2010). Since processes involved in the accumulation and/or the mineralization of SOM can be particularly slow (Diacono and Montemurro, 2010; Rasmussen et al., 1998), the relative importance of soil properties and farm practices on SOC dynamics should be evaluated in long-term experiments.

Green manure and/or crop residues incorporation have been proposed as alternative cropping systems in order to reduce SOC loss when farmyard manure is unavailable (Drinkwater et al., 1998; Zhao et al., 2009). However, these practices are relatively recent and most of the studies regarding the effect of crop residue incorporation on SOC have been performed on relatively short timescales, generally over a decade or two. The long term effect of crop residues incorporation is therefore still under discussion (Liu et al., 2014; Powlson et al., 2011) especially if pedoclimatic conditions are taken into account (Poeplau et al., 2015).

Soil biological communities are particularly sensitive to agricultural practices sustaining SOC (Mäder et al., 2002), as soil SOC is their principal feeding substrate. Biological processes are crucial for the maintenance of soil fertility due to their role in nutrient cycling. For instance, soil biota plays a major role in the mineralization of the SOM, in the fixation of atmospheric nitrogen, or in the reduction of nutrient losses by immobilizing temporarily nutrients in the biomass. In addition, particular biological communities enhance plant nutrient uptake (*e.g.* mycorrhizal fungi) (Johansson et al., 2004) or improve soil texture (*e.g.* earthworms) (Bertrand et al., 2015). As consequence, diversified biological communities in agroecosystems can offer a panel of ecological services that ultimately enhance the sustainability of crop production (Altieri, 1999).

Nevertheless, intensive agricultural practices in conventional farming systems negatively impact the soil biological communities of agroecosystems due to the disturbance induced by chemical fertilizer, pest control measures or soil tillage (Bertrand et al., 2015; Geisseler and Scow, 2014; Zhao et al., 2014). In Switzerland, the DOK ("*biologisch-Dynamische, Organisch-biologische und Konventionelle*") experiment (Mäder et al., 2002) compares the long term effects of different organic and conventional farming systems, but little is still known about the comparative impact of different variants of conventional fertilization management on SOC and biological properties. Therefore, the objectives of the present study were to evaluate the long-term influence of fertilization practices on (i) soil C storage and soil physic-chemical properties, (ii) microbial and earthworm communities and (iii) crop yields. In this study, results of the oldest long-term field experiment in Switzerland, which started in 1963, are presented. In a conventional farming system, the effects of two different organic amendments (farmyard manure application and crop residues incorporation) were compared to the conventional use of mineral fertilizers alone.

2. Materials and methods

2.1. Site description and experimental design

The experiment was established in 1963 by the Swiss Research Station Agroscope in Changins (46°24′5.28″N, 06°14′7.47″E, altitude: 445 m) on a Calcaric Cambisol (FAO classification) characterized by 196 g kg^{-1} of clay, 345 g kg^{-1} of sand, 20.3 g kg^{-1} of SOC and 7.3 of pH in the plough layer (0–20 cm). During the experimental period 1963–2013, mean annual rainfall and temperature were, respectively, 1004 mm and 9.5 °C. Before the establishment of the experiment, the area was covered with grassland (alfalfa field). Winter wheat was planted one year before the beginning of the experiment as a buffer crop. The experimental design has undergone some modifications since its establishment. The original design of the experiment (1963–1970) was a randomized block with three main fertilization practices (FP) and four replications. The three FP were: (i) mineral fertilizers alone (*MIN*), (ii) crop residues incorporation with reduced mineral fertilization (*RES*) and (iii) cattle farmyard manure application (10 t ha^{-1} $year^{-1}$) with reduced mineral fertilization (*FYM*). In 1971, two different levels of mineral nitrogen (N) fertilization were introduced as sub-treatments to all three fertilizer practices, thus converting the experimental design into a split-plot one, where the size of each subplot was 55 m^2 (5 m x 11 m). A dose of 120 kg N ha^{-1} (*N120*), considered optimal according to the Swiss fertilization guidelines for wheat crop (Sinaj et al., 2009), and a limiting dose of 50 kg N ha^{-1} (*N50*) were applied one or two times during the growth period as ammonium nitrate (NH_4NO_3) according to crop type.

2.2. Fertilization and agronomic practices

The crop rotation changed twice over the whole experimental period. Initially a 'wheat-maize-wheat' rotation was established for the 1963–1972 period, followed by the integration of sugar beet from 1972 to 2008, which was then finally replaced by rapeseed in 2008 (Table 1).

At harvest, crop residues were systematically removed from the soil in the case of *MIN* and *FYM* main-treatments, but were incorporated with the plough layer (0–20 cm) for the *RES* main-treatment. *FYM* (composted cattle manure originating from loose housing) was applied at the rate of 10 t ha^{-1} $year^{-1}$ every two or four years (Table 1) and incorporated into the soil with the plough before planting. Finally, the soil was prepared with a rotary harrow (5 cm) for planting.

Phosphorus (P) and potassium (K) fertilizer rates were determined according to the Swiss fertilization guidelines (Sinaj et al., 2009) and were the same for all treatments. The recommended P and K fertilizer rates from the Swiss fertilization guidelines were adjusted (reduced) to account for the contribution from organic amendments (*RES* and *FYM*). The average amounts of P and K applied as mineral fertilizers are reported in Table 1. Triple superphosphate [$Ca(H_2PO_4)_2 \cdot H_2O$] and salt of potash (KCl) were applied prior to planting for the summer crops (maize, sugar beet) and during the growing period for other crops (winter wheat and rapeseed). Herbicides were applied depending on weed pressure, and standard phytosanitary protection was applied according to integrated crop protection principles (Häni et al., 1990).

2.3. Soil sampling and analyses

Soils were sampled in early August 2013, after the harvest of winter wheat, from the plough layer (0–20 cm). Ten cores with a diameter of 2.5–3 cm were randomly taken within each sub-plot. Plant residues were removed from the soil and the individual samples mixed to form a composite sample per plot. Samples were oven-dried at 40 °C during 48 h, sieved at 2 mm and analysed for different soil properties (Table 2).

Soil bulk density was measured in early April 2014. Samples were taken from the central part of each plot away from any wheel track. A single pit was dug for each replicate and 6 cm diameter