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RESEARCH ARTICLE

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The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system

Alexandra Maltas[1] | Hedi Kebli[1] | Hans Rudolf Oberholzer[2] | Peter Weisskopf[2] | Sokrat Sinaj[1]

[1] Agroscope, Nyon 1260, Switzerland
[2] Agroscope, Zürich 8046, Switzerland

Correspondence
S. Sinaj, Agroscope, Nyon 1260, Switzerland.
Email: sokrat.sinaj@agroscope.admin.ch

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Agroscope

Abstract

The effects of mineral fertilizers and organic amendments on soil properties, carbon (C) sequestration, and crop yields are studied in a 37-year field experiment, Phosphorus–Potassium-balanced design, in Switzerland.

Treatments included a control (mineral fertilization) without nitrogen (N) fertilizers (*Min-N0*) and with optimal N (*Min-Nopt)* and 5 organic amendments (green manure [*Gm*], cereal straw [*Str*], fresh cattle manure in 2 doses 35 and 70 t ha^{-1} [*Ma35* and *Ma70*] and cattle slurry [*Slu*]) all receiving the same optimal N fertilization as *Min-Nopt*. All mineral and organic treatments received optimum P–K fertilization.

Nitrogen fertilization (*Min-Nopt* vs. *Min-N0*) increased soil organic C, microbial activity, and microporosity but decreased pH, magnesium, and macroporosity. All organic treatments with optimal mineral N resulted in higher soil organic C content compared with *Min-Nopt*, however, these effects were significant only for the highest dose of manure. The organic amendments supplied 25% to 80% additional C input to the soil compared with *Min-Nopt*, and their amendment-C retention coefficients ranged from 1.6% (*Gm*) to 13.6% (*Ma70*). Chemical, physical, and biological soil properties were not or slightly significantly different among organic treatments. Nevertheless, soils fertilized with farmyard manure produced generally higher grain yield (up to 7.3%) compared with *Min-Nopt* whereas the opposite effect was noted for *Gm* (−2.2%) and *Str* (−5.2%) treatments due to their negative effect on N availability. In conclusion, *Gm* and *Str* treatments were as effectives as *Ma35* and *Slu* treatments to prevent soil degradation but required higher chemical fertilizer to maintain crop yield.

KEYWORDS

crop yields, farmyard manure, green manure, mineral fertilizers, soil organic carbon, soil properties

1 | INTRODUCTION

Soil organic matter (SOM) plays a key role for soil quality by improving soil physicochemical and biological properties (Lal, 2013; Swift, 2001). Therefore, developing a sustainable management of SOM is a major concern for agriculture, environmental quality, and land preservation (Lal, 2009; Paustian et al., 2016).

Agricultural practices may lead to an increase or depletion of SOM in agroecosystems (Edmeades, 2003). Intensive agricultural practices have depleted 25–75% of soil organic carbon (SOC) in most soils of the world (Lal, 2013). But when organic-mineral fertilizations were conducted according to C balance method, usually no substantial depletion of SOC were detected (Körschens et al., 2013). In Switzerland, easily accessible synthetic fertilizers combined with specialization of farms have resulted in a dramatic decrease in the use of farmyard manures. However, the lack of organic matter inputs as farmyard manure causes significant decreases in SOC when no alternative measures are taken (Fließbach, Oberholzer, Gunst, & Mäder, 2007). The importance of SOC for soil quality and health highlights the need to find practices to prevent SOC depletion. Haynes and Naidu (1998) reported in a review that increasing SOM content leads to improvement of soil biological and physical properties.

SOC response to soil use and management is a slow process that can only be evaluated with long-term experiments (Körschens, 2006; Rasmussen et al., 1998). SOC content results from the balance between SOC mineralization and organic C inputs (Follett, 2001). As a result, management practices increasing C inputs, as farmyard manures, green manure, and crop residues incorporation are known to restore SOC content in agricultural soils (Bhattacharya et al., 2016; Drinkwater, Wagoner, & Sarrantonio, 1998; Zhao et al., 2009).

Changes in SOC and crop yield following application of organic amendments have received great attention (Diacono & Montemurro, 2010; Haynes & Naidu, 1998; Maltas, Charles, Jeangros, & Sinaj, 2013). Körschens et al. (2013) assembled results from 20 European long-term experiments (10 to 61 years) and reported that, on average, combined mineral and organic fertilization increased crop yields compared with mineral fertilization alone. However, few studies have compared the long-term effectiveness of different soil conservation practices. For example, Lal (2009) reported in his review that few systematic and long-term studies are designed to assess the impact of harvest residues on SOC concentration, rate of C sequestration, and soil quality. Maillard and Angers (2014) in a meta-analysis including short- and long-term experiments (3 to 82 years) from 49 sites also reported insufficient studies involving liquid manure compared with solid. Furthermore, nitrogen (N), phosphorus (P), and potassium (K) inputs from organic amendments could lead to an overestimation of the effects of SOM conservation practices in an unbalanced NPK fertilized experimental design (Edmeades, 2003). Edmeades (2003) in a meta-analysis reported that organic manure had a greater effect on increasing SOC, biological activity, and soil physical properties compared with mineral fertilizers alone but provided no advantage with regard to crop yield when experiments were NPK balanced.

The objective of this research was to compare the effects of four different organic amendments (cattle solid manure, cattle slurry, mustard green manure, and cereal straw residues) and mineral fertilizers on SOC sequestration, soil properties, and crop yield from a PK balanced 37-year field experiment in a conventional farming system in Switzerland. The aim, in particular, was to answer the question: Are green manures insertion or cereal straws restitution realistic alternatives to prevent soil degradation in stockless farms? Previous results published from the same experiment have highlighted the effect of these organic amendments on crop yield and some soil properties (Maltas, Oberholzer, Charles, Bovet, & Sinaj, 2012). In this study, we discuss the implications of these treatments with regard to C sequestration, soil physical properties, and crop yield based on 3 years of additional data with a focus on organic amendment effects under treatments with optimal N fertilization.

2 | MATERIAL AND METHODS

2.1 | Site description and agronomic practices

The experiment was established in 1976 by the Swiss Research Station Agroscope in Changins (46°23′55.72″N, 06°14′24.72″E, altitude: 442 m) on a Calcaric Cambisol (FAO classification), characterized by 143 g kg^{-1} clay, 475 g kg^{-1} sand, 11.5 g kg^{-1} SOC, and a pH of 7.2 in the plough layer (0–20 cm). During the experimental period 1976–2013, mean annual rainfall and temperature were, respectively, 1,010 mm and 10.4 °C (Figure 1). One year prior to the establishment of the experiment, winter wheat was sown as a buffer crop. A 5- to 6-year rotation has been applied, alternating spring and winter crops, with 2/3 of crops being cereals (Table 1). Before sowing (in September for winter crop and in April for spring crops), soil was always ploughed to 20–25 cm depth, and the seedbed was prepared with a rotary harrow to 5 cm depth. Herbicides were applied depending on weed pressure, and standard phytosanitary protection was applied according to integrated crop protection principles.

2.2 | Experimental design

The experimental design was a split-plot with six main organic treatments and four subtreatments of mineral nitrogen fertilization in four replicates (Maltas et al., 2012). The experiment consisted of 96 subplot, each measuring 4.5 × 20 m. The main six treatments were no organic amendment except rapeseed and maize residues (*Min*), green manure (*Gm*), cereal straw (*Str*), cattle manure (two doses: *Ma35* and *Ma70*), and cattle slurry (*Slu*). After harvest, cereal straw (wheat, barley, or spring oat) were removed from the experimental plots of all treatments except for the *Str* treatment, where straw was incorporated into the soil with shallow stubble cultivation (10–15 cm). Maize and rapeseed straw was incorporated into the soil in all treatments. In the *Gm* treatment, mustard (*Brassica juncea*) was sown as green manure every 2 years after crop harvest in summer and was incorporated into the soil by ploughing just before sowing the spring crop in the following year. From 1976 to 1994, mustard was fertilized with 60 kg ha^{-1} of N but received no N fertilizer since 1994. In the *Ma35* and *Ma70* treatments, fresh cattle manure (35 and 70 t ha^{-1}, respectively) was spread every 3 years before maize and rapeseed (Table 1) and incorporated into the soil with a plough before sowing. In the *Slu* treatment, 60 m^3 ha^{-1} of cattle slurry 1:1 diluted with wash water was spread in spring during the growth period. Cattle slurry was applied every year from 1976 to 1994 and every 3 years thereafter (Table 1). The chemical properties of all organic amendments are presented in Table 2.

The subtreatments represent four levels of mineral N-fertilization. In this article, only the results from the subtreatment ‘no N fertilization’ (*N0*) for the *Min* main treatment, and subtreatment “optimal N fertilization” (*Nopt*) for all main-treatments are presented.

The N optimal dose (*Nopt*) was determined according to the Swiss fertilization guidelines (Sinaj, Richner, Flisch, & Charles, 2009) with no organic amendments. Mineral N doses were the same for each main treatment and differed solely depending on the crop (Table 3). The mineral N fertilizer used was ammonium nitrate (NH_4NO_3) applied two or three times during the growing period. Total P and K fertilization

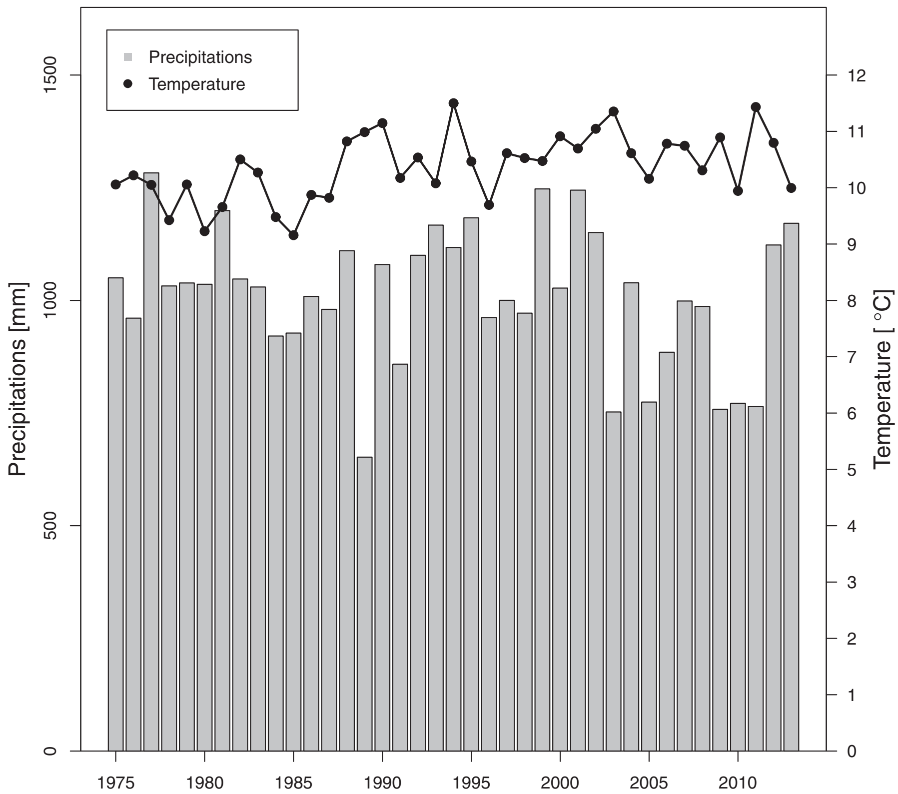

FIGURE 1 Total annual precipitations and mean annual temperatures from 1976 to 2013 at Agroscope in Changins

(mineral and organic) was optimal from 1976 for all treatments, according to the Swiss fertilization guidelines (Sinaj et al., 2009). When farmyard amendments were applied (*Ma35*, *Ma70*, and *Slu*), mineral P and K fertilizers were complimentary to the organic inputs in order to reach the optimal doses (Table 3). Triple superphosphate $[Ca(H_2PO_4)_2. H_2O]$ and potash salt (KCl) were applied at one time prior to sowing for the spring crops (maize, barley, and oat) and during the growing period for winter wheat and rapeseed.

2.3 | Soil sampling and analyses

2.3.1 | Soil sampling

Soils were sampled from the plough layer (0–20 cm) after the wheat harvest in August 2012. At least 10 cores with a diameter of 3 cm were taken randomly within seven treatments: *Min-N0*, *Min-Nopt*, *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, *Ma70-Nopt*, and *Slu-Nopt*. Plant residues were removed from the soil samples, and the individual samples were mixed to form a composite sample per plot. Moist samples sieved at 2 mm were analyzed for biological soil properties and air-dried samples, sieved at 1 mm, used for chemical analysis (Tables 4 and S1). SOC content was measured in 1975, 1987, 1999, 2004, and again in 2012 always after wheat crop harvest.

2.3.2 | Soil organic and chemical analyzes

SOC, total N, pH-water, and cation exchange capacity (CEC) are measured according to the Swiss standard methods (FAL et al., 2011). Soil C stock was estimated using the minimum equivalent soil mass correction (Ellert & Bettany, 1995). Total elements (P, K, Ca, Mg, Cu, Mn, Fe, Zn, and Ni) were measured after dissolution by hydrofluoric and perchloric ($HClO_4$) acids, and sample calcination at 450 °C (as described by the NF X 31-147 standard, Ciesielski, Proix, & Sterckeman, 1997). Available elements (P, K, Ca, Mg, Cu, Mn, Fe, and Zn) were measured after ammonium acetate and EDTA extraction according to the Swiss standard methods (FAL et al., 2011).

2.3.3 | Soil physical analyses

Undisturbed cylindrical soil samples were taken in August 2013 from the central part of each subplot away from any visible wheel track. A pit was dug for each of the four replicates. Cylinders (42 × 55 mm height × diameter) were carefully driven into the soil at depths of 3–7 and 13–17 cm. After cautiously preparing the top and bottom surfaces, the soil samples were wrapped in a plastic bag as protection against moisture loss and stored at 4 °C for further analyses. The values of both depth increments (3–7 and 13–17 cm) were averaged for approximate value at 0–20 cm depth.

To describe the functionality of the pore system more in detail, pore-size classes have been analyzed, with macropores important for the transport of soil solution and gasses, mesopores for the storage of plant available water, and fine pores for establishing the border to soil water not available for plant roots. Bulk density was determined as the ratio 'mass of the oven-dried soil sample: volume of the water-saturated soil sample.'

The different pore classes were determined by weighing the soil samples at defined matric tensions during a desorption process. Macropores (pF < 2 and diameter > 29 μm) were drained to 3, 6, and 10 kPa (corresponding to pF values of 1.5, 1.8, and 2.0 and to

TABLE 1 History of crops rotation and organic amendments application

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
Maize	■ 0 ◊ ♦						■ 0 ◊ ♦						■ 0 ◊ ♦						■ 0 ◊ ♦
Winter wheat		♦				0 ♦		■ ♦				0 ♦		♦				0 ♦	
Spring barley			■ 0 ♦						■ 0 ♦						■ 0 ♦				
Winter rapeseed				0 ◊ ♦						0 ◊ ♦						0 ◊ ♦			
Spring oat					■ ♦						■ ♦						■ ♦		

Note. ■ = Years with mustard sown before spring crops on *Gm* treatment. 0 = Years with cereal straw incorporation on *Str* treatment. ◊ = Years with manure application on *Ma35* and *Ma70* treatments. ♦ = Years with slurry application on *Slu* treatment. Main and subtreatments were interrupted in 2003 and 2004. Crop yield in 2001 were not measured due to physiologic accident.

TABLE 1 Continued

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Maize						■ 0 ◊ ♦					■ 0 ◊ ♦						■ 0 ◊ ♦		
Winter wheat					0								0			0			
Spring barley		■ 0						■ 0											■ 0
Winter rapeseed			0 ◊ ♦											0 ◊ ♦					
Spring oat				■											■				

TABLE 2 Chemical properties of organic amendments

Treatments	Organic amendments	Number of application 1975–2012	Dry matter (t ha^{-1})	Chemical property (kg t^{-1} of dry matter)				Reactivity index[c]
				N-tot	P-tot	K-tot	Mg-tot	
Gm-Nopt	Mustard	17	2.5[a]	28.00[a]	4.40[a]	29.90[a]	2.00[a]	2.28
Str-Nopt	Wheat residue	14	4.4[a]	3.65[a]	0.94[a]	10.47[a]	0.82[a]	1.54
	Oat residue	5	4.3[a]	4.82[a]	1.41[a]	17.40[a]	1.06[a]	—
	Barley residue	5	3.6[a]	5.06[a]	1.18[a]	20.47[a]	0.71[a]	—
Ma35-Nopt	Cattle manure	12	7.3[b]	26.51[b]	7.20[b]	33.30[b]	4.72[b]	0.09
Ma70-Nopt	Cattle manure	12	14.5[b]	26.51[b]	7.20[b]	33.30[b]	4.72[b]	0.09
Slu-Nopt	Cattle slurry	24	2.1[b]	52.06[b]	9.76[b]	83.53[b]	6.77[b]	0.14

[a]Standard value in Switzerland in aboveground biomass for green manure and in straw for cereals (Sinaj et al., 2009).

[b]Mean of measured values from 1976 to 2012. Density assumed for fresh slurry was 1.0 t m^{-3}.

[c]Measured in 2011 and calculated according to Ding, Novak, Amarasiriwardena, Hunt, and Xing (2002) as the ratio between the area of the absorption peak of carbonyl group (carboxylic acid and ketone, 1,725 cm^{-1}) and the sum of the areas of C, H, and N-functional groups (1,450, 1,420, and 779 cm^{-1}).

TABLE 3 Amount of nitrogen (N), phosphorus (P), and potassium (K) in kg ha^{-1} applied as chemical fertilizers from 1976 to 2013

Treatments	Winter wheat			Spring barley and oat			Maize, rapeseed		
	N	P	K	N	P	K	N	P	K
Min-N0	0	31	100	0	31	100	0	31	100
Min-Nopt	125	31	100	70	31	100	130	31	100
Gm-Nopt	125	31	100	70	31	100	130	31	100
Str-Nopt	125	26	66	70	26	66	130	26	66
Ma35-Nopt	125	22	66	70	22	66	130	0	0
Ma70-Nopt	125	0	0	70	0	0	130	0	0
Slu-Nopt	125	0[a] 31[b]	0[a] 58[b]	70	0[a] 31[b]	0[a] 58[b]	130	0	0

[a]From 1976 to 1993.

[b]From 1994 to 2013.

TABLE 4 Effect of organic amendments and N fertilization on selected soil properties in 2012 (0–20 cm)

Soil properties	*Min-N0*	*Min-Nopt*	*Gm-Nopt*	*Str-Nopt*	*Ma35-Nopt*	*Ma70-Nopt*	*Slu-Nopt*
Organic							
SOC (g kg^{-1})	9.12 A	10.57 A b	10.72 b	11.51 b	12.26 b	14.25 a	11.70 b
N_{tot} (g kg^{-1})	1.20 A	1.33 A b	1.33 b	1.40 b	1.50 ab	1.70 a	1.50 ab
C/N	7.60 A	7.94 A ab	8.06 ab	8.22 ab	8.18 ab	8.38 a	7.80 b
C stock (t ha^{-1})	26.81 A	31.06 A b	31.53 b	33.84 b	36.06 b	41.88 a	34.39 b
Biological							
Basal respiration (mg C-CO_2 kg^{-1} soil h^{-1})	0.55 A	0.61 A a	0.63 a	0.58 a	0.60 a	0.66 a	0.61 a
Chemical							
CEC (cmol+ kg^{-1})	7.38 A	7.97 A a	7.85 a	7.85 a	8.19 a	8.48 a	8.58 a
pH-H_2O	7.13 A	6.93 A a	6.50 a	6.90 a	7.00 a	6.80 a	6.90 a
Physical							
Bulk density (g cm^{-3})	1.43 A	1.47 A a	1.41 a	1.43 a	1.42 a	1.36 a	1.40
Total porosity (cm^3 100 cm^{-3})	46.8 A	44.7 B b	47.5 a	45.9 b	46.9 a	48.3 a	47.8a
Macropores at pF 0–2 (cm^3 100 cm^{-3})	17.6 A	14.1 B a	16.2 a	15.2 a	15.9 a	16.6 a	16.4 a
Mesopores at pF 2–4.2 (cm^3 100 cm^{-3})	11.1 A	11.6 A a	11.2 a	11.1 a	11.4 a	10.7 a	10.3a
Micropores at pF > 4.2 (cm^3 100 cm^{-3})	18.0 B	19.0 A a	20.1 a	19.6 a	19.5 a	21.0 a	21.1a

Note. Different uppercase letters within the same row indicate significant difference between *Min-No* and *Min-Nopt* subtreatments at the .05 probability level by Fischer's LSD test. Different lowercase letters within the same row indicate significant difference between main treatments (*Min-Nopt*, *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, *Ma70-Nopt*, *Slu-Nopt*) at the .05 probability level by Fischer's LSD test. CEC = cation exchange capacity; LSD = least significant difference; SOC = soil organic carbon.

equivalent pore diameters of 97, 48, and 29 µm), using a pneumatic tension plate system (pF laboratory station, EcoTech, Bonn, Germany). Mesopores (pF 2.0–4.2 and diameter 0.2–29 µm) and micropores (pF > 4.2 and diameter > 0.2 µm) were drained to 100, 500, and 1,500 kPa (corresponding to pF values of 3.0, 3.7, and 4.2 and to equivalent pore diameters of 2.9, 0.6, and 0.2 µm), using pressure plate systems (500 kPa Pressure Plate Extractor and 1,500 kPa Ceramic Plate Extractor, Soil Moisture Inc., Santa Barbara CA, USA). Total porosity, the total volume of pore space as a percentage of the total volume of the soil sample, was calculated as the sum of macroporosity, mesoporosity, and microporosity.

2.3.4 | Soil biological analyses

Activity of soil microorganisms was estimated as basal respiration by the Isermeyer method and performed according to FAL et al. (2011). Eighty grams of soil sample (dry matter) was incubated for 7 days at 22 °C with a water content corresponding to 40–50% of maximum water holding capacity. Twenty grams of incubated subsamples (dry matter) were weighed into perforated centrifuge tubes. Tubes were inserted into 250 ml screw bottle with 20 ml of 0.025N NaOH solution at the bottom and closed immediately for a 24-hr incubation period. Then, the tubes were changed in another bottle with 20 ml of 0.025N NaOH solution for the final 72-hour of incubation. After the incubation, the alkali was titrated with 0.025N HCl solution. Respiration was calculated based on HCl used (22 mg CO_2 equals 1 ml 1 M HCl).

2.4 | Crop biomass sampling and analyses

The grain dry matter yield was determined each year at harvest according to (FAL et al., 2011). The total aboveground (grains and straws) dry matter yield at harvest was measured in 1977–1979, 1981, 1993, 1995, 1998–1999, 2002–2004, and 2006–2012. To determine total aboveground dry matter, plants were removed from 1 m^2 in middle-part of each plot. For the other years, the aboveground biomass was estimated according to the Swiss standard values for harvest index (ratio of grain dry matter to total aboveground dry matter [Sinaj et al., 2009]).

For all crops and mustard green manure, belowground crop residue C inputs were estimated based on aboveground yield and crop-specific C allocation coefficients (Leifeld, Reiser, & Oberholzer, 2009; Oberholzer, Leifeld, & Mayer, 2014). It was also assumed that 55% of the belowground C input from annual crops is stored in the upper 20 cm of soil (Jackson et al., 1996). Total C inputs were calculated as the sum of crop residues (i.e., belowground plus aboveground left in the field) and organic amendments. In addition, when converting organic matter to organic C, the C fractions of plant dry matter, and the dry matter of farmyard manure and slurry were taken as 0.45 and 0.42 g kg^{-1}, respectively, according to measurements done in 2011–2012 (data not shown).

2.5 | Data analysis

All statistical analyses were performed using R 3.1.1 (R Core Team, 2014). To avoid the interannual variations in crop grain yield, which were often higher than differences between treatments in a given year, a crop yield index was used to compare the results (Morel, Plenchette, & Fardeau, 1992). Thus, results of grain yields were expressed as a percentage of the control treatment (*Min-Nopt*) and were named 'relative grain yields.' The evolution of relative grain yield was assessed using a simple moving average (SMA) curve (Blanchet, Gavazov, Bragazza, & Sinaj, 2016). SMA smooths high interannual variations by taking into consideration the current year and the five previous ones to show the evolution of crop yields at the timescale of the crop rotation. SMA is calculated as the mean of grain yield over 6 years.

One-way analysis of variance was performed to analyze the effects of organic fertilizers and the effects of N fertilization. Data from subtreatments *Nopt* (*Min-Nopt*, *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, *Ma70-Nopt*, and *Slu-Nopt*) were used to analyze organic amendments effects, and data from *Min-N0* and *Min-Nopt* treatments were compared with study N fertilization effects.

When analysis of variance reported significant effect of treatments, treatment means were compared using a posteriori Fisher least significant difference tests of the *Agricolae* R package; differences between means were considered significant at $p < .05$. Pearson correlation coefficient among soil properties and average relative grains yield (1976–2013) across all treatments and replications ($n = 21$) were calculated using the *Corrplot* R package.

3 | RESULTS

3.1 | Evolution of soil organic carbon

After 37 years, the SOC content of the *Min-N0* treatment decreased and increased significantly only for the *Ma70-Nopt* treatment (Figure 2). The other treatments showed similar SOC trends

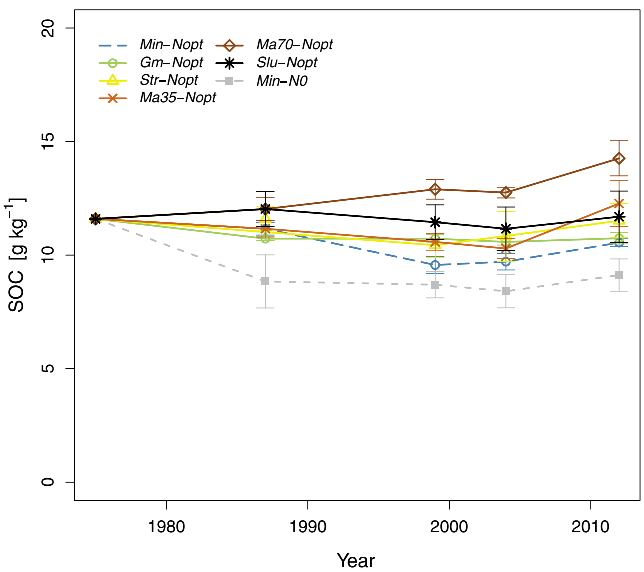

FIGURE 2 Temporal evolution of SOC (0–20 cm) from 1975 to 2012 depending on organic amendment and N fertilization. Vertical bars on each point are the standard error mean. Treatments were no organic amendment except rapeseed and maize residues (*Min-N0 and Min-Nopt*), green manure (*Gm-Nopt*), cereal straw (*Str-Nopt*), two doses of cattle manure (*Ma35-Nopt* and *Ma70-Nopt*), and cattle slurry (*Slu-Nopt*). All treatments have received recommend mineral N fertilization, except the N unfertilized treatment *(Min-N0)*. SOC = soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

compared with 1975, because of the nonsignificant interannual variability. SOC in *Slu-Nopt* and *Ma70-Nopt* treatments were similar until 1987, then the SOC content in *Slu-Nopt* began to decline due to the reduced application of slurry (every 3 years instead of annually, Figure 2).

In 2012, because of the intraannual variability, *Min-Nopt*, *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, and *Slu-Nopt* treatments did not differ significantly (Table 4). Nevertheless, after 37 years, SOC content tended to decrease in the *Min-Nopt* treatment compared with *Str-Nopt*, *Slu-Nopt*, *Ma35-Nopt* ($p > .05$), and *Ma70-Nopt* ($p < .05$).

The absence of N fertilization (*Min-N0*) caused a rapid SOC content decrease during the first 12 years while remains more or less constant until 2012. SOC content measured in 2012 was higher but not significantly different ($p > .05$) in the *Min-Nopt* treatment compared with *Min-N0* treatment (Table 4).

3.2 | Physicochemical and biological soil properties

With respect to physical soil properties, N fertilization had no significant effect on bulk density, however, its effect on total porosity (sum of macroporosity, mesoporosity, and microporosity) was significant (Table 4). Whereas N fertilization increased significantly the volume of micropores (pF > 4.2), the opposite effect was observed for macroporosity (pF < 2.0); the volume of mesopores was not significantly affected by this experimental factor.

Concerning organic treatments, we did not observe any significant effect on soil physical properties (Table 4). Nevertheless, compared with the mineral *Min-Nopt* treatment, organic amendments tended to increase total porosity and thereby the volume of macropores and micropores (Table 4). A significant positive correlation was found between microporosity and SOC content (Figure S1).

There were no significant effects of organic amendments (*Min-Nopt* vs. *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, *Ma70-Nopt and Slu-Nopt treatment*) and N fertilization (*Min-N0* vs. *Min-Nopt treatment*) on soil chemical composition, except for SOC content, total N content, C/N ratio, and available Mg content (Tables 4 and S1). Mineral N fertilization (*Min* treatments) increased SOC (+15.9%) and soil total N content (+10.8%). The highest values of SOC and soil total N were observed for the organic *Ma70-Nopt* treatment and the lowest for the mineral treatment *Min-N0*. Soil C/N ratio was significantly lower in the *Slu-Nopt* treatment compared with the *Ma70-Nopt* treatment. Soil C stock followed similar trends as SOC. Manure and slurry amendments significantly increased available Mg compared with the mineral *Min-Nopt* treatment (Table S1). A positive but nonsignificant effect of *Gm-Nopt* and *Str-Nopt* treatments on available Mg was also observed. There was a significant negative effect of mineral N fertilization on available Mg (*Min-Nopt* treatment vs. *Min-N0* treatment, Table S1).

The effects of organic amendments and N fertilization were not significant ($p > .05$) for soil pH, CEC, and relevant cations, but an increase of CEC and a decrease of the soil pH were observed for the organic amendments (Table 4).

Overall, there were no significant effects of the organic treatments on basal respiration, but treatment *Ma70-Nopt* presented the highest value. A positive but not significant effect of N fertilization was also noted in the *Min* treatment (Table 4).

3.3 | Crop yield

Crop yields increased due to N fertilization (*Min-Nopt* vs. *Min-N0* treatment), however, they decreased over time in the absence of N fertilization (Figure 3). The weakest effect was observed on spring oat and the highest on wheat (Table 5).

On average for 1976–2013 period, treatment with farmyard manure (*Ma35-Nopt*, *Ma70-Nopt*, and *Slu-Nopt*) produced significant higher grain yields (+4 to +7%, Table 5) compared with treatment without organic amendment (*Min-Nopt*).

Farmyard manure had a positive effect on yield the year of application (on maize or rapeseed) and also the 2 years following application (Table 5). This effect increased over time and reached about +10% in 2012 (Figure 3). An opposite trend was observed in the green manure treatment (*Gm-Nopt*), with a yield decrease compared with *Min-Nopt* (Table 5). The negative effect of green manure on crop yield occurred mostly during the period 1994–2013, whereas this effect was not significant for the 1976–1993 period, when N fertilizers were applied along with green manure (Figure 3). Green manure decreased potential yield particularly in the year of incorporation (maize, spring barley, and spring oat), and also for wheat after oat (Table 5). Straw effect on crop yield was also negative but more stable over time, with a mean decrease of 5% (Figure 3, Table 5). This negative effect was observed on all crops except spring oat and was slightly more pronounced on maize, spring barley, and rapeseed crops before which cereal straw had been incorporated into the soil (Table 5).

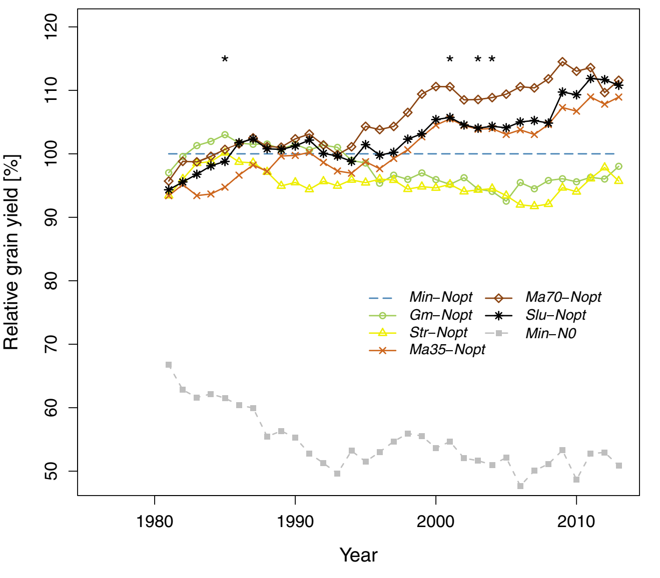

FIGURE 3 Evolution of relative grain yield (%*Min-Nopt*) depending on organic amendment and using 6 years moving average. Asterisks (*) indicate years when the harvest was not conducted or unsuitable due to lodging or climatic events (e.g., flooding). The influence of these years was consequently minimized by using the average value of the previous 5 years [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Effect of organic amendments and N fertilization on grain yield compared with *Min-Nopt* control treatment

Treatments	Period	Maize n^b = 7	Wheat after maize n^b = 6	Spring barley n^b = 6	Rapeseed n^b = 5	Spring oat n^b = 5	Wheat after oat[a] n^b = 6	Mean
Mean dry yield in control treatment (t ha^{-1})								
Min-Nopt	1976–2013	7.72	4.75	4.12	3.06	4.87	5.23	
Relative yield (%*Min-Nopt*)								
Min-N0	1976–2013	67 B	34 B	56 B	54 B	70 B	51 B	**55.2 B**
Min-Nopt	1976–2013	100 A b	100 A bc	100 A b	100 A b	100 A a	100 A ab	**100 A c**
Gm-Nopt	1976–2013	93[c] c	101 ab	99[c] b	101 b	98[c] a	97 bc	**97.8 c**
Str-Nopt	1976–2013	93[c] c	95 c	93[c] c	93[c] c	101 a	95[c] c	**94.8 d**
Ma35-Nopt	1976–2013	104[c] ab	103 ab	107 a	106[c] ab	103 a	101 a	**103.9 b**
Ma70-Nopt	1976–2013	107[c] a	107 a	112 a	109[c] a	106 a	104 a	**107.3 a**
Slu-Nopt	1976–2013	101[c] ab	100 BC	111 a	106[c] ab	103 a	103 a	**103.9 b**
Influence of experimental design modifications on relative yield (%*Min-Nopt*) of *Gm* and *Slu* main treatments								
Gm-Nopt	1976–1993	96[c]	102	103[c]	97	100[c]	99	**99.6**
	1994–2013	91[c]	100	95[c]	104	96[c]	95	**96.0**
Slu-Nopt	1976–1993	99[c]	94[c]	111[c]	104[c]	101[c]	101[c]	**101.5**
	1994–2013	103[c]	106	106	105[c]	118	105	**106.4**

Note. Different uppercase letters within the same row indicate significant difference between *Min-N0* and *Min-Nopt* subtreatments at the .05 probability level by Fischer's LSD test. Different lowercase letters within the same row indicate significant difference between main treatments (*Min-Nopt*, *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, *Ma70-Nopt*, *Slu-Nopt*) at the .05 probability level by Fischer's LSD test. LSD = least significant difference.

[a]Or after wheat in 2007.

[b]Number of years.

[c]Years with amendment application.

4 | DISCUSSION

4.1 | SOC evolution in the soils receiving solely mineral fertilizers

In 2012, after 37 years, SOC content in the control treatment *Min-Nopt* was similar to the initial SOC content. Arable soils in Switzerland (Leifeld et al., 2009; Oberholzer et al., 2014), and more generally in temperate regions (Bellamy, Loveland, Bradley, Lark, & Kirk, 2005; Kutsch et al., 2010), often suffer from a low or still declining SOM content. This decline is frequently related to land-use changes from previous vegetation such as permanent grassland (Oberholzer et al., 2014) or forest (Poeplau et al., 2011). Our experimental site was under cropland for more than 10 years prior to the start of the experiment, thus SOC in the control treatment *Min-Nopt* was perhaps close to its steady state. The necessary quantity of C input to maintain the SOC stock at the initial value (estimated at 3.5 t C ha^{-1} y^{-1}, Figure 4) was close to the C inputs in the control treatment *Min-Nopt* (aboveground residues of maize and rapeseed, and belowground residues of all crops), estimated at 2.7 t C ha^{-1} y^{-1} (Figure 4). The minimum amount of total C inputs needed to maintain SOC in other long-term trials ranges from 2.0 to 5.6 t C ha^{-1} y^{-1} (Johnson, Allmaras, & Reicosky, 2006; Leifeld et al., 2009; Oberholzer et al., 2014), which is in agreement with our results.

4.2 | Effect of organic amendments on SOC evolution

Compared with *Min-Nopt*, the SOC conservation practices supplied 25% to 80% more C to the soil (0.7, 1.4, 1.0, 0.7, and 2.2 t C ha^{-1} y^{-1} for *Gm-Nopt*, *Str-Nopt*, *Ma35-Nopt*, *Slu-Nopt*, and *Ma70-Nopt*, respectively, Figure 4). These higher C inputs were mainly due to direct C input from organic amendments and indirect C input through net primary production. Indirect C input represented only −1.1%, −0.9%, +0.5%, +5.7%, and +6.3% of supplementary C input for *Str-Nopt*, *Gm-Nopt*, *Ma35-Nopt*, *Slu-Nopt*, and *Ma70-Nopt* treatments, respectively (data not shown). Similarly to Maillard and Angers (2014), our results showed a significant linear relationship between the SOC stock increase through organic amendments between 1975 and 2012, and total C input. However, compared with *Min-Nopt*, significant positive effect of organic treatments on SOC content in 2012 was only observed for high manure rates (*Ma70-Nopt*) and this for both analyzed soil horizons 0–20 and 20–50 cm (Table 4 and Table S2). A high surface input of organic matter could favor the production of dissolved organic carbon that can be transported to deeper soil horizons and thus contribute to the subsoil C storage (Lorenz & Lal, 2005). Little or no effect of increased C input on SOC was also noted in other long-term experiments (Lemke, VandenBygaart, Campbell, Lafond, & Grant, 2010; Powlson, Glendining, Coleman, & Whitmore, 2011). Rasmussen et al. (1998) suggested that soil C changes were detectable only after a long time period because of the small yearly inputs of C into a much larger total soil C pool.

Efficiency of organic amendments on C sequestration is related to the amount of C input, but also on its quality. Compared with farmyard manure amendments (*Ma35* and *Slu*), mustard green manure, and cereal straw incorporations (*Gm* and *Str*) provided similar or higher C input (Figure 4). Nevertheless, farmyard manure amendments had a higher effect on SOC content (Figure 4 and Table 4). Other studies have also found that manure or slurry applications had a larger effect on sequestration of organic C in soil than straw incorporation

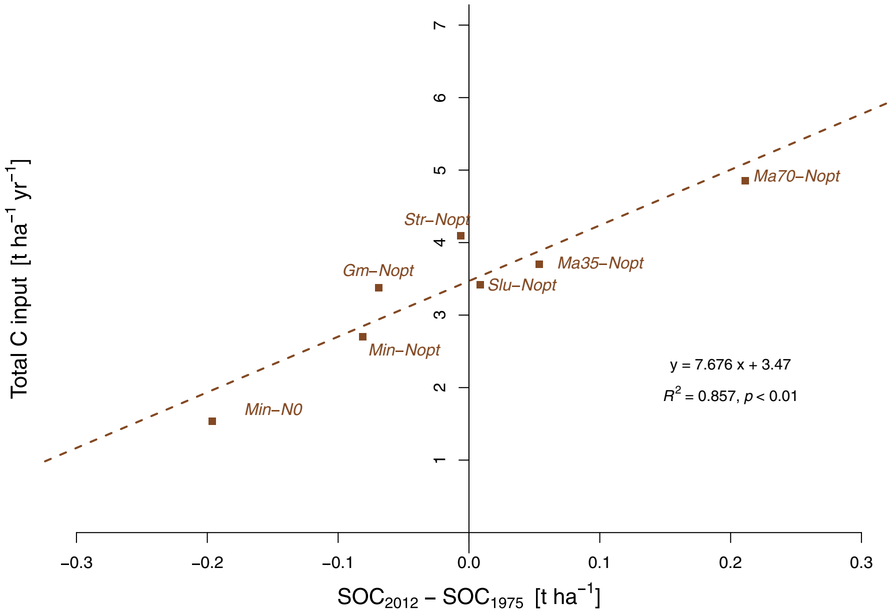

FIGURE 4 Relation between total C inputs (belowground plus aboveground residues left in the field and organic amendments) and evolution of SOC stock between 1975 and 2012. Corrections for differences in bulk density between treatments were done by calculating SOC contents according to the principle of the "equivalent soil mass" with the *Min-Nopt* treatment as reference (Ellert & Bettany, 1995). The initial bulk density was assumed to be equal to bulk density on *Min-c* treatment in 2012, because similar SOC content was observed at both dates. SOC = soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

(Kätterer, Bolinder, Andrén, Kirchmann, & Menichetti, 2011; Thomsen & Christensen, 2010) or green manure (Sauerbeck, 1982). That effect may be related to a reduced mineralization and have therefore a higher amendment-C retention coefficient (also named humification coefficient). The retention or isohumic coefficient is defined as the fraction of applied organic matter that is 'transformed' into SOM (Maillard & Angers, 2014). The amendment-C retention coefficient (ton of C accumulated in the soil per ton of organic C applied, in %) can vary greatly depending on the degradability of the organic input material (Haynes & Naidu, 1998). The coefficient represents the fraction of the C residue that actually becomes stabilized as SOC with longer half-life time in soil (Reiter, 2015). In our study, amendment-C retention coefficients ranged as follows: *Gm-Nopt (1.8%) < Str-Nopt (5.4%) < Slu-Nopt (12.5%) < Ma35-Nopt (13.5%) = Ma70-Nopt (13.6%)*. These results are unique to our study as only few studies have compared liquid manure, solid manure, green manure, and cereal straw. However, our amendment-C retention coefficients are similar to those observed in the literature (Maillard & Angers, 2014). In a recent meta-analysis, Maillard and Angers (2014) estimated a manure amendment-C retention coefficient of 12 ± 4% for an average study duration of 18 years and reported crop residues amendment-C retention coefficients of 6–14% in medium to long-term studies (10–100 years). Amendment-C retention coefficients were negatively correlated to the presence of carbonyl groups (see reactivity index, Table 2). The differences in amendment-C retention coefficients could also be related to the amount of decomposition that has occurred prior to the application of farmyard manures onto the soil. Haynes and Naidu (1998) reported that during composting, breakdown of easily decomposable organic material occurred with subsequent loss of CO_2. As a result, composted organic matter added to soils is relatively more resistant to further breakdown than fresh organic matter. Similar mechanisms may be involved during storage of animal manure before application.

4.3 | Effect of organic amendments on biochemical soil properties

Significant positives correlations were found between SOC content and several bio-chemical soil properties (CEC, Basal respiration, P-tot, Cu-tot, Zn-tot, K-AAE, Mg-AAE, Figure S1). Nevertheless, SOC increases with organic amendments were insufficient to significantly affect biochemical soil properties. Indeed, organic amendments had no significant effect on biological and chemical soil properties except on the available Mg content. In our study, fertilization levels were balanced in terms of P and K but not in terms of Mg. As a result, available Mg in soil increased with manure and slurry application. The positive effect of manure on available Mg has been previously shown due to their high Mg content and also due to improving soil CEC (Edmeades, 2003; Sienkiewicz, Krzebietke, Wojnowska, Zarczynski, & Omilian, 2009). Farmyard amendments (manure and slurry) also contain micronutrients and trace elements due to the supplements in animal feeds, which could increase soil Cu, Zn, Fe, Cd, and Pb contents (Li et al., 2010). Although in our study, such effects were not detectable in 2012 for available Zn, Fe, Cu, Mn.

4.4 | Effect of organic amendments on physical soil properties

Soils receiving organic amendments presented slightly (but not significant) better physical soil properties (bulk density, total porosity) than soils receiving solely mineral fertilizers. Several authors have also shown that long-term addition of organic matter improves soil porosity and decrease bulk density (Celik, Ortas, & Kilic, 2004; Diacono & Montemurro, 2010). According to Haynes and Naidu (1998), the effects of organic matter additions could be due to (a) a dilution effect caused by mixing the added organic material with the denser mineral fraction of the soil and (b) higher soil aggregation (more intense biological activity and SOM-clay binding).

As a result of decreased bulk density with organic matter inputs, pore size distribution is altered. Number of macropores and micropores increased whereas mesoporosity was not significantly affected. Similar effects of organic amendments on macroporosity and microporosity were also reported by other researchers (Aggelides & Londra, 2000; Gupta, Dowdy, & Larson, 1977; Haynes & Naidu, 1998). The increase in macroporosity was generally linked to greater aggregation and earthworm activity whereas microporosity increase could be related to the high specific surface area of organic matter (Haynes & Naidu, 1998).

In return, microporosity can act as a physical protection of SOC against microorganism (Bachmann et al., 2008) and could participate to SOC sequestration. Change distribution of pore sizes affects soil water properties. Indeed, macropores are of great importance in infiltration, mesopores are important for the storage of plant available water, and micropores store water unavailable for plants (Pająk & Krzaklewski, 2007). Higher microporosity led to better water-holding capacity at both field capacity (pF ≈ 2) and wilting point (pF > 4.2). Thus, SOC content enhancement lead to greater water retention capacity but no change in water availability (pF 2–4.2) as observed by others as well (Olness & Archer, 2005; Rawls, Pachepsky, Ritchie, Sobecki, & Bloodworth, 2003).

4.5 | Effects of nitrogen fertilization on soil properties

A nonsignificant but positive effect of N fertilization (*Min-N0* vs. *Min-Nopt* treatments) was observed on SOC content and consequently on CEC and biological activity. Nitrogen fertilization has been reported to increase C sequestration (Lemke et al., 2010; Liebig, Varvel, Doran, & Wienhold, 2002), but the effect differs between studies (Blanchet et al., 2016; Khan, Mulvaney, Ellsworth, & Boast, 2007; Maltas et al., 2012). The application of fertilizers to nutrient deficient soils generally increases SOC content because fertilizers increase crop production and thereby the amount of plant residues released to the soil (Edmeades, 2003).

Our results also indicate that N fertilization significantly decreases available Mg content in soil. Nitrogen fertilization probably increased Mg exports from soil due to higher crop yield (Sinaj et al., 2009).

The effects of N fertilization on microbial activity differed between studies. Some authors suggested that the absence of N could reduce microbial decomposition activities (Green, Blackmer, & Horton, 1995), whereas others (Marschner, Kandeler, & Marschner, 2003; Ramirez, Craine, & Fierer, 2012) suggested that nitrogen addition could modify microbial community structure and enhance their ability to decompose recalcitrant carbon substrates. Our results confirm these findings, as we observed a positive but not significant effect of N fertilization on microbial activity.

Total soil porosity also decreased when N fertilization was applied. N fertilization increased significantly the volume of micropores due to SOC improvement but the opposite effect was observed for macropores. Macroporosity decrease could be resulted from reduced root biomass, earthworm activity, or clay flocculation. Nevertheless, more complex experiments are required to provide accurate assessments on these effects.

4.6 | Effect of organic amendments on crop yields

Soils amended with farmyard manure (*Ma35-Nopt*, *Ma70-Nopt*, and *Slu-Nopt*) generally produced higher grain yields compared with soils receiving only mineral fertilizers (*Min-Nopt*), whereas the opposite effect was noted with green manure (*Gm-Nopt*) and straw incorporation (*Str-Nopt*). A combination of inorganic fertilizer and organic manure has improved yields in many parts of the world (Rasmussen et al., 1998). Körschens et al. (2013), summarizing results from 20 European long-term field experiments, concluded that the combination of organic and mineral fertilizers resulted in a 6% yield benefit compared with mineral fertilization alone. Nevertheless, Edmeades (2003) reported that the positive effect of manure on crop yields is only assessed based on the nutrients provided by the manure. This suggests that manures and mineral fertilizers, when applied at equivalent rates of N, P, K, have generally similar effects on crop yields (Edmeades, 2003). The results of our study with optimal N and PK balanced treatments were partially in agreement with the findings of these authors. In our study, the farmyard manure had a positive effect on crop yield. N provided by farmyard manure was probably responsible for a part of this effect since, the positive effect of farmyard manure decreased with increasing mineral N fertilization and with the number of years after application of amendment (Figure S2). But this positive effect increased from 1976 to 2013 indicating also the positive influence of the SOM content increase.

Negative effects of the *Gm-Nopt* treatment occurred mostly during the year with green manure incorporation and were probably related to lower N availability, as we did not observe this effect when N fertilizers were applied on mustard green manure (1976–1993 period). Indeed, N uptake by the green manure could deplete plant available soil mineral N for the next crop. Other mechanisms such as reduced soil moisture (due to the increased transpiration by the green manure) or secretion of allelopathic substances by the mustard plants (Vaughn & Boydston, 1997) could also be involved in yield decrease.

The slightly negative influence of crop residue incorporation on crop yield is in accordance with previous studies (Christian & Bacon, 1991; Nyborg, Solberg, Izaurralde, Malhi, & Molina-Ayala, 1995) but contradicts others that reported yield increases (Lehtinen et al., 2014; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004). Lehtinen et al. (2014), in a meta-analysis, reported that crop residue incorporation resulted in a 6% average yield increase compared with crop residue removal and attributed this to the SOC increase. Negative effects of straw incorporation observed in our study could be due to lower N-supply for crops because decomposition of straw induces N-immobilization at the start of the decomposition process (Cheshire et al., 1999; Kätterer & Andrén, 1999). Cereal straw could also transfer pathogens to other cereals in the rotation (Berzsenyi, Győrffy, & Lap, 2000) thus affecting crop yield.

5 | CONCLUSION

SOC content tends to increase with organic amendments used in this study, but this effect was only significant for very large inputs (70 t ha^{-1}) of fresh cattle manure. After 37 years, the total C input from organic amendments (mustard green manure, cereal straw residues, 35 t ha^{-1} of fresh cattle manure, and cattle slurry) was insufficient to observe a significant increase of SOC. As a result, only slight effects on physicochemical and biological soil properties were observed. However, the focus of this study was on the surface horizon (0–20 cm), which did not provide a full picture of the impacts that organic amendments may have had on the overall SOC stock. Nevertheless, opposing effect of treatments on crop yields were noted: a positive effect of treatments with farmyard amendments (manure or slurry) and a negative effect of green manure or cereal straw incorporation. These negative effects on crop yields were likely due to reduced N availability for plants. This study highlights the benefit of using farmyard manure compared with other organic fertilizers on SOC management and soil quality preservation. Further investigations are required to better quantify the long-term effects of organic amendments on SOM quality.

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ORCID

Sokrat Sinaj http://orcid.org/0000-0003-0848-2270

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SUPPORTING INFORMATION

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