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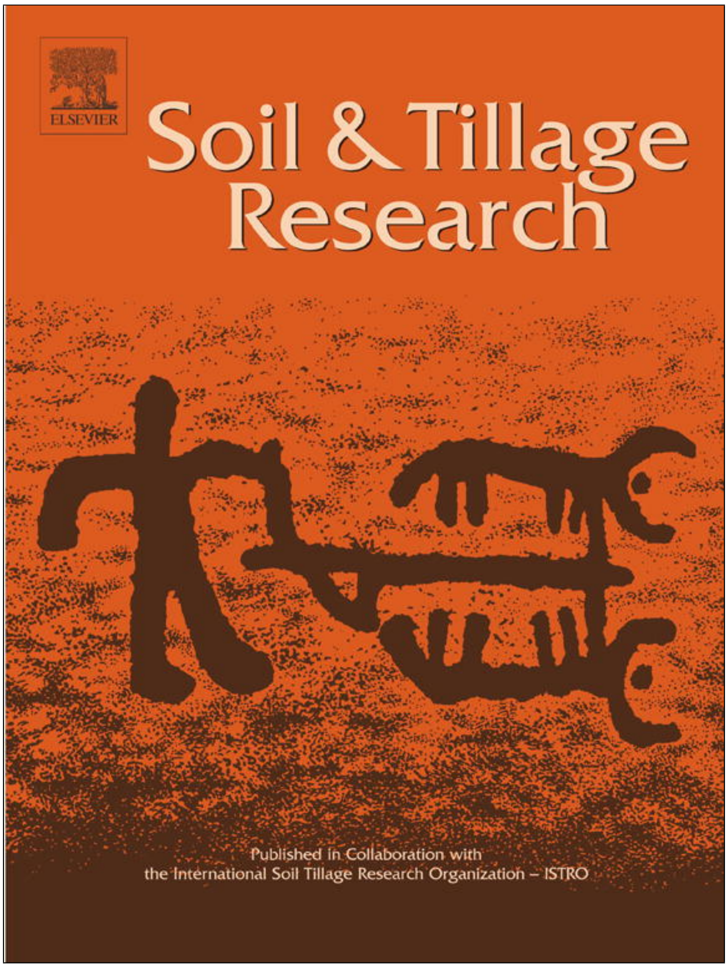

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Effect of organic fertilizers and reduced-tillage on soil properties, crop nitrogen response and crop yield: Results of a 12-year experiment in Changins, Switzerland

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ABSTRACT

The combined effects of the nature of fertilizers (chemical and/or organic), splitting of manure inputs and tillage intensity (reduced or conventional) on soil properties, crop production and crop response to nitrogen (N) fertilization were studied in Changins, Switzerland between 1997 and 2009. Five main-treatments were tested in a split-plot design: (i) mineral fertilizer with reduced-tillage (MinRT), (ii) manure every year plus mineral fertilizer with reduced-tillage (Ma1RT), (iii) manure every year plus mineral fertilizer with conventional-tillage (Ma1CT), (iv) manure every three years plus mineral fertilizer with reduced-tillage (Ma3RT) and (v) slurry every year plus mineral fertilizer with reduced-tillage (Slu1RT). Sub-treatments included two levels of N-fertilization: an optimal dose (according to the Swiss fertilization guidelines) and a sub-fertilization (60% of the optimal dose). The soil was a Calcaric Cambisol with, in 1997, 20.5 g kg^{-1} of soil organic matter (SOM) in the first twenty centimeters. After twelve years of experimentation, SOM contents were 19.8, 20.3, 21.3, 21.5, and 22.8 g kg^{-1} under respectively Ma1CT, MinRT, Ma1RT, Slu1RT and Ma3RT treatments. The main-treatments do not have a significant effect on SOM contents and chemical soil properties. When N-fertilization was non-limited (optimal dose) and manure was applied, tillage intensity had not significant effect on grain yield. When N-fertilization was non-limited with reduced tillage (RT), the crops in the treatments with organic fertilizers yielded 2–13% more grains (0.2, 0.3, 0.4 and 0.5 t ha^{-1} more for respectively rapeseed, spring cereal, maize and winter wheat) than those in treatments with mineral fertilizers only. The sub-fertilization (60% of the optimal dose) decreased the grain yields by 9, 13, 15, 7 and 16%, respectively, in MinRT, Ma3RT, Ma1RT, Ma1CT, Slu1RT. In conclusion, organic fertilizers and reduced tillage provide effective means to conserve soil fertility and crop production in the studied soil, although both enhance N fertilizer needs. Splitting manure applications into lower amounts annually did not bring any benefits to soil properties or crop production.

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1. Introduction

The use of organic fertilizers is considered to be an effective way of increasing soil organic carbon (SOC) sequestration and supplying micronutrients to crops in comparison with the use of mineral fertilizers only (Lal, 2009). Long term cultivation without organic fertilizers usually leads to a decrease in SOC and total N contents (Dick, 1992) and in crop yield (Bhandari et al., 2002; Regmi et al., 2002). However, with the increased accessibility to chemical fertilizers and farm specialization, the use of organic fertilizers has declined dramatically in some regions of Switzerland over the last decades. This raises the question of the maintenance of soil organic matter (SOM) content on farms without livestock (Vullioud et al., 2006).

SOM is a key component of the agrosystem as it prevents soil degradation, reduces the risk of water pollution and enhances chemical, biological and physical soil properties (Swift, 2001). Consequently, improvement in the SOM content generally leads to an increase in agronomic productivity through a better use of energy-based inputs (e.g., fertilizers, water, pesticides) (Lal, 2011). Changes in the SOM content may also alter the potential of soil to supply or sequester nutrients, especially N, through changes in mineralization–immobilization turnover (Jansson and Persson, 1982) and cation exchangeable capacity (Lal, 2006).

The build-up of SOC is a slow process depending on the amount of carbon (C) input to soil as crop residue, and its balance with SOM decomposition (Nyborg et al., 1995). Cropping systems affect SOC levels because of their effects on C inputs and C losses (Follett, 2001). In general, application of organic fertilizers and especially manure, either alone or in combination with mineral fertilizers, increases SOC content (Blair et al., 2006; Gong et al., 2009; Maltas et al., 2012; Manna et al., 2007; Rudrappa et al., 2006;). In contrast,

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inorganic fertilizers often produce contradictory effects on SOC content (Ghani et al., 2003; Gong et al., 2009; Simon, 2008). This uncertainty is partly attributed to the specific processes governing C sequestration under agronomic practices, varying with soil type, climate and crop rotation. No-till (NT) is generally known to improve SOM content (Bayer et al., 2006; Bernoux et al., 2006; Campbell et al., 1999; Follett, 2001; Franzluebbers, 2005; Lal et al., 1998; Lal, 2009; Six et al., 2002; Tebrügge and Düring, 1999; West and Post, 2002), especially in the plowed soil layer (Baker et al., 2007; Ogle et al., 2005; Puget and Lal, 2004), because of changes in soil structure and lower decomposition rates due to physical protection of C within aggregates (Jastrow et al., 1996; Six et al., 2000). However, other studies questioned whether NT actually increases SOC content (Angers et al., 1993, 1997; Anken et al., 2004; Baker et al., 2007; Christopher et al., 2009; Franzluebbers and Arshad, 1996; Wright et al., 2005). The storage capacity of SOM in these systems varies widely depending on soil characteristics (texture, slope), climatic conditions, initial SOM content, differences in C inputs from crop production and C decomposition in the soil and management practices (Balesdent et al., 2000; Collins et al., 2000; Doran and Smith, 1987; Paustian et al., 1997). Numerous studies have also shown that NT can increase or decrease crop yields (Al-Kaisi et al., 2005; Beyaert et al., 2002; Dam et al., 2005; Drury et al., 2003; Griffith et al., 1988; Halvorson et al., 1999; Hammel, 1995; Hussain et al., 1999; Potter et al., 1996; Tarkalson et al., 2006; Wilhelm and Wortmann, 2004) depending on environmental conditions and have varying impact on C inputs to soil (Ogle et al., 2012).

Since long-term effects of agricultural management practices vary greatly among sites conditions, it is necessary to evaluate these effects under different soil–climatic conditions (Johnston, 1997; Mitchell et al., 1991). The objective of the present study was to quantify, for a Cambisol and under the relatively dry climate of western Switzerland, the medium-term effect (12 years) of organic fertilization and reduced-tillage practices on soil properties, crop yield and crop response to N fertilization. The questions addressed were: (i) how the nature of organic fertilizers, the splitting of manure application and the tillage intensity affect SOM content, and (ii) what are the consequent effects of these practices on soil chemical properties, crop N response and crop yield.

2. Material and methods

2.1. Site description and experimental design

A field experiment was established in 1997 by the Swiss Research Station Agroscope ACW (46°24′E, 06°13′N; altitude: 445 m) on a Calcaric Cambisol with 230 g kg^{-1} of clay and 410 g kg^{-1} of silt in the twenty uppers centimeters of soil. Mean annual rainfall and temperature were, respectively, 954 mm and 10 °C (means from the last 30 years). Before starting the experiment, the area was covered with spring barley. Some selected physico-chemical characteristics are presented in Table 1.

The experimental design was a split-plot with five main-treatments, two sub-treatments and four replications. The five main-treatments were: (i) mineral fertilizer with reduced-tillage (MinRT), (ii) manure every year plus mineral fertilizer with reduced-tillage (Ma1RT), (iii) manure every year plus mineral fertilizer with conventional tillage (Ma1CT), (iv) manure every three years plus mineral fertilizer with reduced-tillage (Ma3RT) and (v) slurry every year plus mineral fertilizer with reduced-tillage (Slu1RT). Sub-treatments included two levels of nitrogen fertilization: an optimal dose (N100) and a sub-fertilization (N60). The optimal dose was determined according to the Swiss fertilization guidelines (Sinaj et al., 2009). On the treatment N100, crop N needs calculated according to Sinaj et al. (2009) were assumed to be 100% covered by mineral and/or organic fertilizer (25% of the organic nitrogen is considered available for the crop the year of application and 15% the following year). On the treatment N60, chemical N fertilizer was reduced to cover only 60% of N needs (amount of organic fertilizer is identical to N100 treatments). The chemical N fertilizations (NH_4NO_3) were applied in two or three times during the growing period.

Table 1
Selected soil characteristics in the five main-treatments at the beginning of the experiment (1997, 0–20 cm depth, values in brackets indicate the standard deviation).

Soil characteristics	MinRT	Ma1RT	Ma1CT	Ma3RT	Slu1RT	Mean	Probability
SOM[a] (g kg^{-1})	20.8 (1.3)	20.0 (2.4)	19.8 (2.6)	21.0 (1.4)	20.8 (1.5)	20.5	0.86
pH-H_2O[a]	7.9 (0.2)	7.8 (0.2)	7.8 (0.2)	7.9 (0.1)	7.9 (0.1)	7.9	0.56
P-AAE[a,b] (mg kg^{-1})	136 (31)	124 (32)	124 (30)	145 (33)	133 (25)	132	0.85
K-AAE[a,b] (mg kg^{-1})	195 (14)	190 (22)	193 (14)	216 (33)	199 (37)	198	0.65

[a] Analyzes performed according to the standards methods of the Swiss research stations Agroscope (FAL et al., 2004).
[b] P-AAE and K-AAE represent P and K extracted with ammonium acetate and EDTA.

Table 2
Mean chemical fertilization (kg ha^{-1}) applied on N100 sub-treatment from 1997 to 2008.

Year	Crop	MinRT			Ma1RT			Ma1CT			Ma3RT			Slu1RT		
		N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
1997[a]	Rapeseed	147	35	66	135	22	66	135	22	66	124	22	66	147	35	66
1998	Spring oats	89	18	66	68	6	22	68	6	22	72	6	22	81	18	66
1999	Winter wheat	138	17	79	111	5	29	111	5	29	138	0	0	141	9	0
2000[a]	Maize	130	0	0	105	0	0	108	0	0	93	0	0	118	0	0
2001	Spring wheat	150	82	242	130	54	0	130	48	0	128	70	116	137	85	216
2002	Spring Barley	90	10	74	71	10	54	71	10	34	90	10	74	79	14	100
2003[a]	Rapeseed	145	42	140	119	18	2	119	18	5	97	0	0	134	37	105
2004	Winter wheat	140	0	0	118	0	0	118	0	0	114	0	0	135	0	0
2005	Maize	115	55	173	79	0	83	79	0	102	115	52	44	104	55	143
2006[a]	Winter wheat	164	0	0	104	0	0	104	0	0	112	0	0	107	0	0
2007	Winter wheat	140	55	0	77	0	0	77	0	0	110	11	0	92	55	0
2008	Rapeseed	141	0	0	117	0	0	117	0	0	141	0	0	117	0	0

[a] Year with application of manure on Ma3RT.

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Table 3
Organic fertilizers characteristics (mean content for the period 1997–2008, values in brackets indicate the standard deviation) and inputs by organic fertilizer on Ma1RT and Ma1CT with 12 t ha^{-1}, Ma3RT with 36 t ha^{-1} and SluRT with 22 m^3 ha^{-1}.

	Manure	Slurry	Ma1RT/Ma1CT	Ma3RT	SluRT
	mg kg^{-1} of fresh matter		kg ha^{-1}		
Dry matter	210.0 (92.1)	25.3 (18.6)	2520	7560	557
Organic matter	143.2 (19.8)	20.0 (16.0)	1718	5155	440
Total N	4.6 (1.4)	1.4 (0.7)	55	166	31
N–NH_4	0.2 (0.1)	0.8 (0.3)	2	7	18
Total P	1.5 (1.3)	0.2 (0.2)	18	54	4
Total K	6.0 (3.5)	1.7 (0.6)	72	216	37
Total Ca	7.1 (8.5)	0.8 (0.4)	85	256	18
Total Mg	1.0 (0.7)	0.2 (0.2)	12	36	4

Analyzes performed according to the standards methods of the Swiss research stations Agroscope (FAL et al., 2004). Moisture content of manure was 80%. Density assumed for slurry was 1.0.

2.2. Fertilization and agronomic practices

The crop rotation, over a period of five to six years, alternated spring and winter crops, and included 60–70% of cereals, rapeseed and maize (Table 2).

At harvest, straw from the cereals was systematically removed from the soil, whilst straw from maize (2000 and 2005) and rapeseed (1997, 2003 and 2008) was incorporated into the soil. After harvesting the previous crop, shallow stubble cultivation (10–15 cm) was performed with a cultivator. Before sowing, a second tillage was carried out with a cultivator (10–15 cm in treatments with reduced-tillage) or a plough (20–30 cm in treatment with conventional tillage). Finally, the soil was prepared with a rotary harrow (5 cm) for sowing.

Manure was applied at a rate of 12 t ha^{-1} every year on Ma1RT and Ma1CT and 36 t ha^{-1} every three years (in 1997, 2000, 2003 and 2006) on Ma3RT. Cattle manure from loose housing was used. This was spread and incorporated into the soil before sowing. Cattle slurry was diluted (1:1) with wash water and sprayed in spring during the period of growth. The characteristics of the manure and slurry are presented in Table 3.

The total phosphorus (P) and potassium (K) fertilizations (mineral and organic) were optimal on all main-treatments, according to the Swiss fertilization guidelines for crops and grassland (Sinaj et al., 2009). When organic fertilizers were applied (Ma1RT, Ma1CT, Ma3RT and Slu1RT), mineral P and K fertilizers completed the organic inputs to reach the optimal doses. The average amounts of P and K applied as chemical fertilizers in the different treatments are presented in Table 2. Superphosphate and salt of potash (KCl) were applied prior to sowing for the summer crop (maize) and during the growing period for other crops (rapeseed, winter and spring cereals).

2.3. Soil sampling and analyses

Soils were sampled in September 2009, after the rapeseed harvest, from the plough layer (0–20 cm). At least 10 cores with a diameter of 2.5–3 cm were taken randomly within each sub-plot. Plant residues were removed from the soil and the individual samples mixed to form a composite sample per plot. These samples were air-dried, sieved at 2 mm and analyzed for different soil properties (Table 4).

The total aboveground dry matter of crops (grains and straw) was measured each year at harvest. The harvest was dried at 65 °C for 48 h (FAL et al., 2004). The N content of aboveground dry matter was analyzed each year from 1998 to 2008.

Table 4
Effects of the main and sub-treatments on soil properties in 2009.

Analyze	N60 subplot Mean of all main treatments	N100 sub-plot					
		Mean	MinRT	Ma1RT	Ma1CT	Ma3RT	Slu1RT
Organic properties							
SOM[a] (g kg^{-1})	21.1A	21.1A	20.3ab	21.3ab	19.8b	22.8a	21.5ab
Total N[a] (g kg^{-1})	1.58A	1.60A	1.58ab	1.60ab	1.48b	1.70a	1.63ab
C/N ratio	7.7A	7.7A	7.5a	7.7a	7.8a	7.8a	7.7a
Chemical properties							
pH-H_2O[a]	7.9A	7.9A	8.0a	7.8a	7.9a	8.0a	7.9a
CEC[a] (cmol + kg^{-1})	11.2A	11.3A	11.1a	11.3a	11.0a	11.4a	11.7a
Base saturation (%)	94.0A	94.5A	96.0a	91.7a	95.7a	94.3a	94.8a
Total P[b] (mg kg^{-1})	955.3A	943.2A	956.8a	911.5a	909.4a	978.6a	959.9a
Organic P[b] (mg kg^{-1})	286.0A	287.7A	263.8a	321.1a	269.1a	285.2a	299.4a
P-AAE[c] (mg kg^{-1})	126.3A	123.2A	120.5a	118.8a	105.2a	140.0a	131.8a
K-AAE[c] (mg kg^{-1})	168.4A	167.8A	160.0a	174.3a	154.7a	177.4a	172.7a
Mg-AAE[c] (mg kg^{-1})	191.7A	195.5A	213.2a	185.5a	224.4a	176.1a	178.6a
Ca-AAE[c] (g kg^{-1})	19.5A	19.7A	24.6a	15.7a	23.9a	16.8a	17.4a
Cu-AAE[c] (mg kg^{-1})	10.2A	10.6A	10.9a	7.3a	10.6a	13.8a	10.2a
Fe-AAE[c] (mg kg^{-1})	323.5A	322.1A	337.5a	340.8a	346.0a	305.3a	280.8a
Mn-AAE[c] (mg kg^{-1})	427.0A	416.9A	422.0a	433.3a	419.5a	441.3a	419.0a
Zn-AAE[c] (mg kg^{-1})	3.1A	3.3A	2.8a	3.3a	3.3a	3.1a	3.2a

[a] SOM, total N, pH-water and CEC are measured according to the Swiss standard methods (FAL et al., 2004).
[b] Total and organic-P are measured after soil incineration at 550 °C during 1 h and extraction of the ashes with 0.5 M H_2SO_4 (Saunders and Williams, 1955).
[c] P-, K-, Mg-, Ca-, Cu-, Fe-, Mn- and Zn-AAE are extracted with ammonium acetate and EDTA according to the Swiss standard methods (FAL et al., 2004).
Different uppercase letters within the same row indicate significant difference between sub-plots at the 0.05 probability level by Fisher's multiple range test. Different lowercase letters within the same row indicate significant difference between main-plots at the 0.05 probability level by Fisher's multiple range test.

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2.4. Data analyses

To avoid any inter-annual variations in yield, often higher than those observed in a given year between treatments, a crop yield index was used to compare the results (Morel et al., 1992).

Thus, results of grain yields, aboveground biomass and aboveground N uptake were expressed as a percentage of the control (MinRT) and were mentioned as relative grain yields, relative aboveground biomass and relative aboveground N uptake. In this latter instance, years were considered as a random factor.

The drop in grain yields, caused by the 40%-reduction of N fertilization (N60), has been quantified, each year, using Eq. (1):

$$y = 100 \times \left[1 - \frac{x\text{N}60_i}{x\text{N}100_i}\right] \quad (1)$$

where y represents grain yield response to N fertilization (in %), $x\text{N}60_i$ the grain yield on the N60 sub-plot of the main-plot i and $x\text{N}100_i$ the grain yield on the N100 sub-plot of the main-plot i.

The same equation was used to calculate the aboveground biomass response and the aboveground N uptake response to N fertilization.

Statistical analyses were accomplished using the program Xlstat 2010, copyright Addinsoft 1995–2009. A two-way ANOVA was performed to analyze the effects of main-treatments and sub-treatments (split-plot design) on soil properties in 2009. Effects of main-treatments on relative grain yields, aboveground biomass and aboveground N uptake under N100 sub-treatments were tested by a two-way ANOVA (crop × main-treatment). Four crops were defined: rapeseed, winter wheat, spring cereal and maize. The same test was applied to analyze responses to N fertilization of grain yields, aboveground biomass, and aboveground N uptake. After calculating ANOVA, when $P < 0.05$, the Fisher multiple-range test was applied to compare significance differences within main-treatments or sub-treatments. Linear regression was performed with Sygmaplot 11.0, copyright Systat Software 2008, to describe the temporal change in the aboveground N uptake response to N fertilization (Fig. 2).

3. Results and discussion

3.1. Organic soil properties

On the N100 sub-treatments of the five main-treatments, SOM contents in 2009 (Table 4) were not significantly ($P < 0.05$) different compared to SOM contents in 1997 (Table 1). Thus under conditions of the present study, the application of 12 t ha^{-1} of manure every year (Ma1CT) was sufficient to maintain SOM content when the soil was conventionally-ploughed. When only mineral fertilizers were used (MinRT), the reduced tillage (RT) seems to be also effective to conserve SOM content. Nevertheless, it is difficult to detect losses or gains in SOM content over short- and medium-term because of temporal and spatial variability of the studied site (Bosatta and Ågren, 1994).

In 2009, when RT was applied, the nature of fertilizer had not significant effect on the SOM content (Table 4). However, in comparison with 1997, SOM content tends to increase when organic fertilizers were used (+1.3, +1.8 and +0.7 g kg^{-1} under Ma1RT, Ma3RT and Slu1RT, respectively, Tables 1 and 4) while it tends to decrease with mineral fertilizer only (−0.5 g kg^{-1} under MinRT, Tables 1 and 4). Edmeades (2003) reported that, in relation to mineral fertilizers, organic fertilizers increased SOM contents, since they contain significant amounts of organic matter.

When manure was applied every year, soil tillage intensity had not significant effect on the SOM contents measured in 2009 (Table 4). However, in comparison with 1997 the SOM content tends to increase under RT (Ma1RT) while it does not evolve in the case of conventional-tillage (Ma1CT, Tables 1 and 4). These results confirm those of Berner et al. (2008) who suggested that reduced tillage systems may provide a valid option for sequestering soil organic carbon under Swiss conditions. The increase in SOM content in reduced-tillage systems is generally due to lower losses by run-off and mineralization (Six et al., 2002; Tebrügge and Düring, 1999; West and Post, 2002) or to a dilution effect (Franzluebbers, 2002; Yang and Wander, 1999).

Splitting the applications of manure into annual doses (Ma1RT) rather than applying the total amount every three years (Ma3RT) did not significantly affect the SOM content (Table 4). Organic matter in slurry form is generally more easily degradable than in manure (Rudrappa et al., 2006; Su et al., 2006) and therefore has less effect on SOM storage than manure (Triberti et al., 2008). However, in this trial, manure and slurry applied annually (Ma1RT and Slu1RT) presented equivalent SOM contents in 2009 (Table 4), despite the higher input of fresh organic matter with manure than with slurry (Table 3).

It is generally accepted that nitrogen fertilization helps to sequester C in the soil by increasing biomass crop residues (Liebig et al., 2002; Paustian et al., 1997; Raun et al., 1998). However, no significant effect of nitrogen fertilization on the SOM-content was observed from the present study. Indeed, twelve years of different levels of N-fertilization (N60 and N100) did not significantly influence SOM contents (Table 4) whereas reduced N-fertilization decreased aboveground biomass production by only 10% on average in this experiment (Table 6). Numerous studies in the United States, listed by Khan et al. (2007), have also shown little effect of N fertilization on C-storage in soil. It is possible that N-fertilization stimulates microbial activity (Conde et al., 2005; Green et al., 1995; Khan et al., 2007) and/or accumulates more labile organic forms (Stevens et al., 2005) that may be responsible for enhancing SOM mineralization. Furthermore, effect of N fertilization on SOM content depends on the crop residues management. Here, only crop residues of rapeseed and maize have been returned to the soil. In this condition, reduction of N fertilization reduced crop residues restitutions (rapeseed and maize) by, on average, 3.9 t ha^{-1} between 1997 and 2009 (data not shown).

The effects of main-treatments and sub-treatments on total N contents (Table 4) were similar to those reported for SOM content. The C/N ratio, which is an indicator of SOM quality, was not significantly affected by main- and sub-treatments ($P > 0.05$).

3.2. Chemical soil properties

No significant effect of main- and sub-treatments was observed on chemical soil properties, even after 12 years of trials (Table 4). Sub-treatment had also not significant effect on CEC and soil pH (Table 4). However, the application of ammonium-fertilizers generally decreased soil pH and, consequently, the CEC due to nitrification of NH_4^+ and/or the uptake of NH_4^+ by the crops (Pernes-Debuysera and Tessier, 2004). In the experiments presented here, the main- and sub-treatments were probably not applied long enough (12 years) to observe any significant effects on CEC and soil pH.

The organic fertilizers used in this experiment provided significant amounts of P, K Ca and Mg (Table 3) and probably some trace elements, due to their presence in livestock feed (Li et al., 2007). The P and K content of organic fertilizers have been taken into account in the calculation of P and K fertilization (Sinaj et al., 2009). This explains why total, organic and available P (AAE-P), as well as available K (AAE-K), were not significantly affected by the main-treatments (Table 4). Repeated supplies of Ca, Mg and trace elements through organic fertilizers did not significantly

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Table 5
Effects of the main treatments on mean relative grain yield, aboveground biomass and N uptake on N100 sub-plots (MinRT = 100%).

	Relative grain yield (%)		Relative above-ground biomass (%)		Relative N uptake (%)	
Rapeseed						
MinRT	100 (3.3)[a]	A	100 (12.6)[a]	A	100 (175)[b]	A
Ma1RT	105	A	102	A	92	A
Ma1CT	102	A	116	B	119	B
Ma3RT	101	A	100	A	91	A
Slu1RT	108	A	98	A	90	A
Treatment	$P = 0.157$		$P = 0.012$		$P = 0.011$	
Winter wheat						
MinRT	100 (5.1)[a]	A	100 (9.8)[a]	A	100 (141)[b]	A
Ma1RT	106	B	108	AB	107	AB
Ma1CT	110	BC	110	BC	110	BC
Ma3RT	105	AB	110	BC	103	AB
Slu1RT	115	C	117	C	117	C
Treatment	$P < 0.001$		$P = 0.003$		$P = 0.001$	
Spring cereal						
MinRT	100 (4.5)[a]	A	100 (7.6)[a]	A	100 (104)[b]	A
Ma1RT	102	A	104	A	107	A
Ma1CT	96	A	100	A	98	A
Ma3RT	105	AB	106	AB	108	A
Slu1RT	115	B	114	B	120	B
Treatment	$P = 0.013$		$P = 0.030$		$P = 0.005$	
Maize						
MinRT	100 (7.5)[a]	A	100 (19.7)[a]	A	100 (231)[b]	A
Ma1RT	103	A	116	A	117	A
Ma1CT	98	A	99	A	97	A
Ma3RT	103	A	110	A	113	A
Slu1RT	110	A	109	A	118	A
Treatment	$P = 0.235$		$P = 0.212$		$P = 0.103$	
Mean						
MinRT	100	A	100	A	100	A
Ma1RT	104	A	107	B	106	A
Ma1CT	102	A	107	B	106	A
Ma3RT	104	A	107	B	104	A
Slu1RT	113	B	110	B	113	B
Treatment	$P < 0.001$		$P = 0.011$		$P = 0.025$	
Crop	$P = 0.046$		$P = 0.061$		$P = 0.008$	
Crop × treatment	$P = 0.396$		$P = 0.002$		$P < 0.001$	

[a] Absolute value in $t\,ha^{-1}$.
[b] Absolute value in $kg\,N\,ha^{-1}$.
Different letter between treatments for the same crop in a column indicate significant difference at the 0.05 probability level by Fisher's multiple range test.

affect their available forms in the soil (AAE-extraction) in 2009 (Table 4). This result contradicts that of Edmeades (2003), who reported an accumulation of Ca and Mg in the top soil layer following repeated applications of manure and slurry, and the results of Li et al. (2007) which showed higher values of extractable trace elements in soil receiving organic fertilizers. In the present study, the amounts of Ca, Mg and trace elements provided by the manure or slurry in available form (AAE-extraction) are probably (i) offset by higher exports by harvested crops in treatments receiving manure or slurry (Table 5), (ii) accumulated in non-available forms or (iii) lost by run-off or leaching below 20 cm depth.

3.3. Relative grain yields, above-ground biomass and N uptake

When nitrogen is not a limiting factor (N100 sub-treatment), main-treatments have a significant effect on relative grain yield of winter wheat and spring cereal (Table 5). Looking at average results from the 12-year study period, the relative grain yield was significantly higher in the main-treatment receiving slurry annually (Slu1RT) compared to the control receiving only mineral fertilizers (MinRT). When the soil was not ploughed, the relative grain yield tended to be higher in treatment with manure (Ma1RT and Ma3RT, Table 5). Many authors (Bhandari et al., 2002; Ladha et al., 2003; Regmi et al., 2002) have also noted that continued use of mineral fertilizers alone results in lower yields, while the use of organic fertilizer combined with appropriate NPK mineral fertilization helps to maintain them. This positive effect of organic fertilizer on yield is generally due to a gradual improvement of soil physical properties (Zhang et al., 2009). However, the cumulative effect on SOM content alone cannot account for this observation, since (i) the effect of nature of fertilizer on SOM was not significant and (ii) the positive effect of slurry was observed from the beginning of the trial and did not increase with time (Fig. 1). Thus, the positive effect of slurry on grain yield seems rather due to a direct effect, like a more diversified mineral fertilization (e.g. Ca, Mg, trace elements).

On average over the twelve years of the experiment, reduced-tillage did not significantly affect the relative grain yield (Ma1RT vs. Ma1CT, Table 5). Lal (2006) reports an increase in wheat and maize yields with increased organic C content in the soil. Over the twelve years of the present study, the slight increase in SOM content due to reduced tillage had no positive effect on the relative crop yield (Fig. 1). However, such an effect could be expected in the longer term.

Splitting manure applications (Ma1RT vs. Ma3RT) had no significant effect on the relative grain yield, whereas the nature of the organic fertilizer (Ma1RT vs. Slu1RT) did show a significant effect (Table 5). Slurry presented higher values than manure, probably due to the greater proportion of rapidly available nutrients (Rudrappa et al., 2006; Su et al., 2006).

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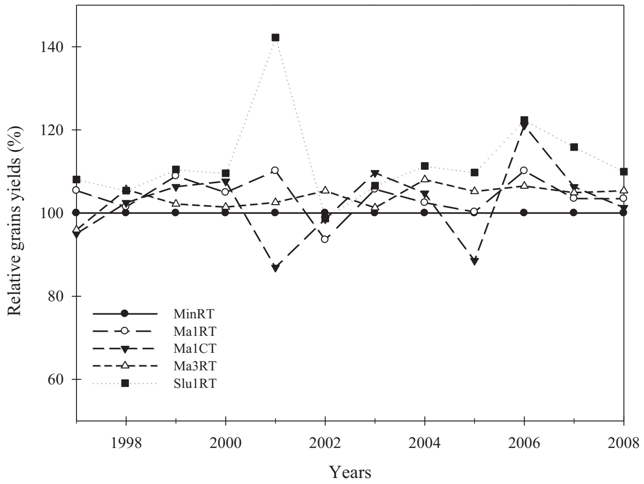

Fig. 1. Evolution from 1997 to 2008 of the relative grain yields (expressed as percentage of MinRT) on N100 sub-treatments. MinRT: closed circle with solid line; Ma1RT: open circle with long dashed line; Ma1CT: closed triangle with medium dashed line; Ma3RT: open triangle with short dashed line and Slu1RT: closed square with dotted line.

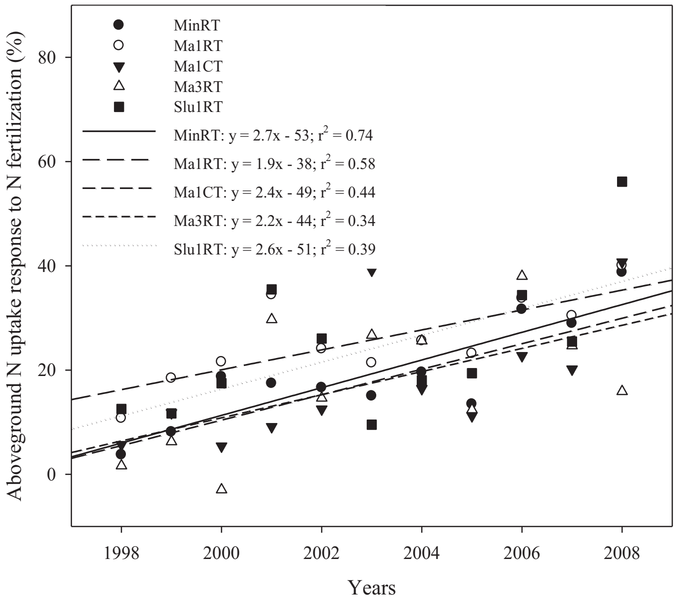

Fig. 2. Evolution from 1997 to 2008 of above-ground N uptake response to N fertilization. MinRT: closed circle with solid line; Ma1RT: open circle with long dashed line; Ma1CT: closed triangle with medium dashed line; Ma3RT: open triangle with short dashed line and Slu1RT: closed square with dotted line.

Effects of main-treatments on relative aboveground biomass (grains and straw) and aboveground N uptake were similar to those reported for relative grain yields (Table 5). However, the interactions between main-treatments and crop species showed significant differences (Table 5). The high requirements with regards to seed-bed quality (Vullioud and Mercier, 2004) could explain the decrease in rapeseed aboveground biomass when the soil was not ploughed. The opposite effect of reduced tillage was observed for maize. This negative effect of tillage on maize has been previously reported by Vullioud and Mercier (2004). A greater water availability in the summer under reduced-tillage, due to lower soil evaporation (Munawar et al., 1990), could be one explanation, while soil compaction caused by tillage, generally in spring when the soil is still wet, could be another. The present study (Table 5) and other Swiss research (Anken et al., 2004; Rieger, 2001; Vullioud and Mercier, 2004) did not show any significant effect of tillage on the yield of winter cereals.

3.4. Response to N fertilization

Main-treatments had a significant effect on the response of grain yield to N fertilization, whereas no significant interaction between main-treatments and crop species was observed (Table 6).

When the soil was not tilled, crops receiving manure annually (Ma1RT, Slu1RT) gave a higher yield response to N fertilization than those receiving only mineral fertilizer (MinRT, Table 6) suggesting greater N needs of crops when manure is used. This result is in contradiction with the findings of Lal (2006) and Whalen et al. (2001), who advocated reduced inputs of N fertilizer, due to higher mineralization, when manure is regularly applied. In this study, SOM was not significantly affected by nature of fertilizer (Table 4) while crop yields were affected when N was supposed not to be a limiting factor (N100, Table 5). On N100, the N uptake by crops and aboveground biomass were greater in treatments with slurry and tended to be higher with manure (Table 5). The higher relative aboveground biomass in these treatments (Table 5) probably increases the crop requirement for N.

The presented data show that the crop response to N fertilization is significantly lower in conventionally tilled plots (Ma1CT vs. Ma1RT, Table 6). This is probably due to the higher soil N availability in the case of ploughing. Indeed, tillage stimulates the mineralization of SOM by an effect (i) on the oxygenation of the soil (Balesdent et al., 2000) and (ii) on the SOM protection inside the soil aggregates (Balesdent et al., 2000; Paustian et al., 2000; Six et al., 2002). Thus, shortly after conversion to no-till, the soil-N availability generally decreases (Balesdent et al., 1990; Kristensen et al., 2000). However, in the longer-term, the contrary could be observed thanks to the gradual increase in the amounts of SOM and the stock of mineralizable-N (Balesdent et al., 2000, Rice et al., 1986). In the Cerrado region of Brazil, Maltas et al. (2007) reported

Table 6
Grain yield, aboveground biomass and aboveground N uptake response to N fertilization (relative difference N100 to N60).

	Response to N fertilization (%) of					
	Grain yield		Aboveground biomass		Aboveground N uptake	
MinRT	9.4	AB	8.5	A	19.3	A
Ma1RT	14.9	C	11.5	A	24.5	A
Ma1CT	6.8	A	6.5	A	16.8	A
Ma3RT	12.9	BC	10.4	A	17.5	A
Slu1RT	15.8	C	11.5	A	23.6	A
Main-treatments	$P < 0.001$		$P = 0.376$		$P = 0.066$	
Crop	$P = 0.003$		$P = 0.091$		$P < 0.001$	
Crop × main-treatments	$P = 0.350$		$P = 0.306$		$P = 0.384$	

Different letter between treatments for the same crop in the same column indicate significant difference at the 0.05 probability level by Fisher's multiple range test.

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that when soils were converted from conventional to no-tillage systems with cover-crops, N mineralization increased along the years through increase in soil total N. The results from this study suggest that N-fertilization should be increased at least during the first twelve years of transition from conventional to reduced tillage (Fig. 2).

The grain-yield and the aboveground biomass responses to N fertilization were not significantly influenced by manure splitting (Ma1RT vs. Ma3RT, Table 6). The N-uptake response tends to be negatively affected by manure splitting. In all cases, splitting of manure applications into smaller doses did not improve manure-N efficiency (Table 6) and is therefore not profitable.

4. Conclusion

In order to maintain the sustainability of cropping systems, preventing the decrease of SOM content is a key factor. Under the conditions of the present study, the application of 12 t ha^{-1} y^{-1} of manure seems to be an effective way to conserve SOM content when the soil was conventionally ploughed (Ma1CT) or reduced-tillage and mineral fertilizers were used (MinRT). Twelve years of experimentation were not long enough to show significant effects of organic fertilizers and reduced-tillage on SOM content and soil chemical properties.

Compared to chemical fertilizers alone, organic fertilizers improved grain yields by 2–13% under non limiting N conditions, probably due to a diversified mineral nutrition. Compared to conventional tillage, reduced tillage did not show any significant effect on grain yields.

Furthermore, both slurry application and reduced-tillage increased crop response to N fertilization which suggested higher N fertilizer needs. This may be due to an increased biomass potential in organic fertilizer systems and to decreased soil N mineralization in reduced-tillage systems.

The splitting of manure applications into annual doses would not appear to be profitable for farmers, since splitting requires more time and increased costs of spreading without giving any benefits to soil properties or crop yields.

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