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Long-term effects of crop succession, soil tillage and climate on wheat yield and soil properties

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ABSTRACT

Climate change is increasing crop losses and yield variability with impacts for global food security. In this context, conservation agriculture appears as a potential solution to maintain crop productivity, soil fertility and environmental sustainability. Therefore, understanding the combined effects of soil tillage and crop succession over a long period is of primary interest. In this study, we analyzed data from a 50 year long-term field experiment to assess (i) the change of climatic parameters, wheat yield and soil organic carbon (SOC) content; (ii) the combined effects of crop succession (monoculture *vs.* crop rotation) and soil tillage system (minimum tillage *vs.* plough) on wheat yield, SOC content and other soil properties at three soil depths (0–10, 10–20 and 20–50 cm); and (iii) the relative contributions of climatic parameters, wheat phenology and agricultural practices on wheat yield variability. Wheat yield was 16% higher in crop rotation compared to monoculture, while soil tillage system had no significant effect on wheat yield during the period 1977–2016. Despite a SOC content decline over time, which was especially marked during the first ten years of the study, SOC content was 7% higher in the minimum tillage treatment compared to the plough treatment, while crop rotation had no significant effect. In 2016, after 50 years of experimentation, both crop succession and soil tillage systems influenced soil properties. Over the 50-year period, the climatic conditions around the heading phase explained 22% of yield variability, while 18% of this variability was explained by crop succession and 6% by the growing degree days until heading stage. In a context of conservation agriculture promotion, our long-term field experiment provides key evidence that the combination of both minimum soil tillage and crop rotation improves soil fertility and crop productivity.

1. Introduction

Climate change may increase crop losses and yield variability (FAO, 2016; Hawkins et al., 2013; Tubiello et al., 2007), which may lead to an increase in price volatility threatening food security and nutrition (FAO, 2016; Lobell et al., 2011). Increasing our knowledge regarding the effects of agricultural practices is essential to develop sustainable cropping systems, *i.e.* systems that ensure stable crop productivity while minimizing soil degradation (Van Eerd et al., 2014). In this context, conservation agriculture appears as a potential solution to maintain crop productivity, soil fertility and environmental sustainability based on three main principles: (i) direct planting of crop seeds with minimum soil disturbance, (ii) permanent soil cover and (iii) crop diversity (FAO, 2011). Therefore, understanding the combined effects of soil tillage and crop succession is of primary interest to promote conservation agriculture.

The impact of no tillage on crop yield is controversial (Pittelkow et al., 2015b). Some studies report similar yields in reduced or no-till systems compared to the conventional plough system (Büchi et al., 2017; Pittelkow et al., 2015b), while others report a decrease in yields (Alvarez and Steinbach, 2009; Pittelkow et al., 2015b). Some of the negative impacts related to the implementation of no tillage, such as the immobilization of nitrogen (Alvarez and Steinbach, 2009), are short-term responses that attenuate or disappear with time (Brouder and Gomez-Macpherson, 2014). Under certain conditions, crop yield is increased when no-till is combined with crop residue management and

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crop rotation (Pittelkow et al., 2015a), fertilization (Alvarez and Steinbach, 2009) or cover crops (Büchi et al., 2018). No till systems may have potential advantages over conventional systems under certain soil, climate and management conditions (Martínez et al., 2008; Pittelkow et al., 2015b). For example, similar or higher crop yields have been observed in crops grown with rainfed conditions under dry climates (Martínez et al., 2008; Pittelkow et al., 2015b; Taner et al., 2015; Wang et al., 2007). In contrast, no-till systems appears less appropriate under humid climates where higher yields are observed in conventional tillage (Martínez et al., 2008; Pittelkow et al., 2015b). Additionally, the responses of crop yield to no-till vary within a region depending on the annual precipitation (*i.e.* wet *vs.* dry year) (Wang et al., 2007). The effects of soil tillage also depend on the initial soil properties. For example, soil tillage can be beneficial on degraded soil to prepare seedbeds and increase crop yield in the short-term but, on the opposite, can reduce soil organic matter content in the long term (So et al., 2009). Crop yield responses to no-till are also influenced by the type of crop, whether it is cereals, oilseeds or legumes (Pittelkow et al., 2015b). For instance, maize and rice were reported to be negatively affected by no-till practices in South and South East Asia (Pittelkow et al., 2015b).

Surprisingly, the impacts of tillage systems are generally focused on the average production while little attention is given to the yield stability (Knapp and van der Heijden, 2018; Macholdt and Honermeier, 2017). In a climate change context, farmers could be more concerned about the yield stability than the level of production (Macholdt and Honermeier, 2017). This is a relevant topic since yield stability can increase or decrease in the long term depending on the selected agronomic practices. Crop rotation generally increases crop yield and yield stability (Helmers et al., 2001). For instance, crop rotations with a higher share of cereals show a reduced yield stability of wheat compared to rotations including legumes (Macholdt and Honermeier, 2017). Moreover, a recent meta-analysis reported that the temporal stability of no-tillage systems did not differ significantly from that of the conventional tillage (Knapp and van der Heijden, 2018).

Regarding soil properties, reduced tillage has many beneficial effects including preservation of soil fertility and biological activity, as well as a reduction in soil compaction, erosion and run-off (FAO, 2011; Mbuthia et al., 2015; McDaniel et al., 2014; Six et al., 2002; Tiemann et al., 2015). For example, Song et al. (2016) reported an increased soil organic carbon (SOC) sequestration in rice-wheat rotation system cultivated with zero-tillage and straw incorporation compared to conventional plough system. Several studies reported that SOC content, as an indicator of soil fertility, is increased through conservation tillage systems and crop diversification (Hobbs et al., 2008; Mbuthia et al., 2015; Tiemann et al., 2015). However, the impact of conservation tillage on SOC remains an ongoing debate (Song et al., 2016) and must be evaluated with long-term experiments (Maltas et al., 2013; Blanchet et al., 2016; Büchi et al., 2017; Triberti et al., 2016) as changes in soil properties over time are slow (Maltas et al., 2018).

Crop growth may be affected by short-term extremes in precipitation and temperature occurring at crucial stages of crop development (Gornall et al., 2010; Holzkämper et al., 2014). Generally, previous studies focused on the impacts of soil tillage or crop succession along with other agricultural practices such as fertilization treatments (Blanchet et al., 2016; Büchi et al., 2017; Maltas et al., 2013; Song et al., 2016), neglecting the potential impacts of shifts in climatic conditions. To ensure future food security, crops adapted to changing environmental conditions are required (Ray et al., 2015; Villegas et al., 2016). Moreover, farmers seek for low variability of crop production from year to year to reduce income risk (Osborne and Wheeler, 2013). Therefore, understanding the links between climate variability and crop productivity is crucial for assessing the resilience of agricultural systems to future climatic conditions (Ceglar et al., 2016; Leng and Huang, 2017). But, to date, few research has focused on how climatic variations affect crop yields and how they are related over time (Ray et al., 2015). Chmielewski and Potts (1995) reported that long-term changes (from 1854 to 1967) in crop yields in the famous Rothamsted field-trial were partially related to the climate variability of the study site. Another study carried out in India forecasted a decline in wheat production by 8.3%, 6.6% and 12.9% respectively for years 2020, 2060 and 2100 due to climate variability (Mor, 2017). Additionally, a recent study highlighted that the production of double-rice in China is being threatened by increasing climatic variability (Liu et al., 2016). However, to our knowledge, no previous long-term study assessed the combined impact of both soil tillage, crop succession and shifts in climatic conditions on crop yield and soil properties.

In this study, we analyzed data from a long-term field experiment carried out from 1967 to 2016 in western Switzerland to assess (i) the evolution of climatic parameters, wheat yield and SOC content over a 50-year period; (ii) the combined effects of crop succession (monoculture *vs.* crop rotation) and soil tillage (minimum tillage *vs.* plough) on wheat yield, SOC content and other soil properties; and (iii) the relative contributions of climatic parameters, wheat phenology and agricultural practices on wheat yield variability.

2. Materials and methods

2.1. Site description and experimental design

The experiment was established in 1967 on a natural meadow by the Swiss Research Station Agroscope in Changins (46°24′N, 06°14′E; 430 m a.s.l), Switzerland. The soil of the study site is a Calcaric Cambisol (IUSS Working Group WRB, 2006), characterized by 253 g kg^{-1} clay, 485 g kg^{-1} sand, 19.2 g kg^{-1} SOC and a pH of 6.4 in the plough layer (0–20 cm). During the experimental period from 1967 to 2016, mean annual precipitation and air temperature were 994 mm and 10.2 °C, respectively (50-year average, data from MeteoSwiss, www.meteoswiss.admin.ch).

During the first 10-year period, from 1967 to 1976, winter wheat (*Triticum aestivum* L.) was grown in monoculture with two soil tillage treatments: minimum tillage *vs.* plough. From 1977, two other crops were introduced: rapeseed (*Brassica napus* L.) and maize (*Zea mays* L.). Thereby, the trial design additionally compared wheat monoculture with wheat in a four-year rotation (wheat-rapeseed-wheat-maize), where winter wheat was present every second year in all treatments. Crop rotation provided information on the combined effects of crop succession and soil tillage on wheat yield. The experimental set-up corresponds to a randomized blocks design with two factors (crop succession and soil tillage) replicated four times. Each of the 16 plots had a size of 148 m^2 (18.5 m × 8 m).

2.2. Soil tillage and crop management

A mouldboard plough followed by a rotary harrow was used in the plough treatment. The implementation of minimum tillage was usually carried out by a rotary harrow with horizontal axis. Depending on weed pressure, soil moisture and the crop to be sown, minimum tillage was sometimes replaced by direct sowing (from 1967 to 1974 as well as in 1979, 1985 and 1987). Due to a high weed pressure, minimal tillage was replaced by ploughing in 1990, 1994, 1998 and 2002.

Winter wheat was seeded with an experimental seeder at 2–4 cm depth and at density of 450 grains m^{-2}. Fertilizers were applied according to Swiss fertilization guidelines (Sinaj et al., 2017). As the fertilization was not investigated in this experiment, all plots received the same amount of phosphorus (20 kg P ha^{-1} and $year^{-1}$) and potassium (55 kg K ha^{-1} and $year^{-1}$). Nitrogen (N) fertilization was adapted to the specific requirements of each crop. Crop protection was performed according to the principles of integrated crop protection for pests and weeds (ASIAT, 1989). Herbicides were always applied to the whole experiment. No fungicide protection was used except for the years 1994, 1996, 2000, 2012, when wheat was protected against eye-spot (*Cercosporella herpotrichoides*) equally in all treatments. No insecticide or growth regulator were applied in this experiment and crop residues were always left on the field.

2.3. Wheat varieties

Winter wheat varieties were kept as long as possible over time and three wheat varieties were used throughout the study: Probus (1967–1976), Zénith (1977–1992) and Arina (1993–2016). Probus, the main variety used in Switzerland until 1976, is a tall variety susceptible to lodging, powdery mildew (*Blumeria gramimis*), stripe and leaf rust (*Puccinia striiformis f.*sp. *tritici, Puccinia recondita*) (Collaud et al., 1991). Zenith was the first semi-dwarf variety registered in Switzerland and remained as the main variety from 1977 to 1984. Due to its good resistance to lodging, this variety accompanied the intensification of cereal production in Switzerland despite its sensitivity to Septoria (*Zymoseptoria tritici*) (Collaud et al., 1991). Susceptible to lodging, leaf rust and stripe rust (Collaud et al., 1991), Arina is very resistant to Fusarium *(Fusarium graminearum, F. culmorum)* and glume blotch (*Parastagonospora nodorum*) and was the dominant variety in Switzerland from 1985 to 2005.

2.4. Data collection

2.4.1. Climatic parameters

Climatic data was collected from the MeteoSwiss station of Changins (46°24′E, 06°14′N; 435 m a.s.l.), 450 m away from the trial site. The resolution and the variables measured were limited during the first part of the study (1967–1976). Therefore, two datasets were collected. The first dataset, from 1967 to 1976, included variables measured at an annual resolution: mean temperature (°C), minimum temperature (°C), maximum temperature (°C) and total rainfall (mm). The second dataset, from 1977 to 2016, included variables measured at a daily resolution: mean temperature (°C), maximum temperature (°C), minimum temperature (°C), cumulative rainfall (mm) and solar radiation (Mj m^{-2}). This higher resolution of the climatic data enabled a more precise assessment of how rotation and soil tillage impacted wheat yield under various climatic conditions.

We additionally calculated several climatic variables as a proxy to more extreme conditions. We defined “climate extreme” as “the occurrence of a value of a climate variable above or below a threshold value near the upper or lower ends of the range of observed values of the variable” (IPCC, 2012). More specifically, we defined “climate extremes” as absolute thresholds of temperature ($T = 25$ °C and $T = 0$ °C) above or below which there is an impact on wheat productivity and quality (Fossati et al., 2014). This approach has previously proved to be useful in explaining growth responses of spruce and beech to simulated climate change (Sanginés de Cárcer et al., 2017).

According to Wheeler et al. (2000), only a few days with extremely high temperatures during the flowering stage can drastically reduce crop yield. Also, frost events during wheat development (*e.g.* during anthesis) may have a negative impact on wheat yield (Alzueta et al., 2014). Thus, we assessed the effects of climate on wheat yield variability considering the environmental conditions during periods of time which include key stages of wheat development (Table 1). More specifically, we defined a period which spanned from the sowing date to the heading date (vegetative period), a second period which included the four weeks following the heading stage (reproductive period), and a third period which included the last two weeks prior harvest, when grain filling and maturation mainly occurs (Table 1).

2.4.2. Wheat yield

From 1967–2016, wheat was harvested at maturity by a combine harvester on a width of 2.40 m on the whole plot length. Grain moisture was measured shortly after harvest, and grain yield adjusted to 14% humidity.

2.4.3. SOC and soil properties

SOC content was measured occasionally since the beginning of the experiment at 0–20 cm soil depth, resulting in a total of 16 values over the period 1967–2016. At least eight cores with a diameter of 3 cm were taken randomly within each plot. Plant residues were removed from the soil and individual core samples were mixed to form one composite soil sample per plot. Soil samples were air-dried and sieved (2 mm) prior to analyses.

In 2016, a full campaign of soil analyses was conducted on all treatments. Soil samples were taken at three soil depths (0–10, 10–20 and 20–50 cm) in August 2016, after the harvest of winter wheat, in the same way as described above. Soil samples were oven-dried at 55 °C during 72 h, sieved at 2 mm and analyzed for the following soil properties: pH-water (pH-H_2O), cation exchange capacity (CEC), SOC, total nitrogen (N_{tot}), total (P_{tot}) and organic phosphorus (P_{org}), total potassium (K_{tot}), total calcium (Ca_{tot}), total magnesium (Mg_{tot}), total copper (Cu_{tot}), total iron (Fe_{tot}), total manganese (Mntot), total zinc (Zntot), and available forms (P_{NaHCO3}, K_{AA}, Ca_{AA}, Mg_{AA}, Cu_{DTPA}, Fe_{DTPA}, Mn_{DTPA}, Zn_{DTPA}). CEC, pH, SOC and all elements, except P_{org} (Saunders and Williams, 1955) and P_{NaHCO3} (Olsen et al., 1954), were measured according to the Swiss standard methods (Agroscope, 2011). P_{min} represents the difference between P_{tot} and P_{org}. The carbon (C) to nitrogen (N) ratio C:N was obtained by dividing SOC by N_{tot}. Bulk density was determined in one soil pit per plot at four different depths: 2–7 cm, 12–17 cm, 25–30 cm and 35–40 cm. Steel cylinders (radius: 5 cm, height: 5 cm, volume: 471 cm^3) were used to take intact soil cores, which were then dried for 72 h at 105 °C and weighted. Bulk density results from the 25–30 cm and 35–40 cm cylinders were averaged to represent the value of the 20–50 cm layer. The 2–7 cm and 12–17 cm cylinders were used to represent the 0–10 cm and 10–20 cm layers, respectively. Bulk density was calculated according to the formula: mass of the oven-dried soil sample / volume of the water-saturated soil sample, and expressed as g cm^{-3} (Maltas et al., 2018).

2.5. Data analysis

Statistical analyses were performed using the R Studio software (R Development Core Team, 2014). When necessary, data were transformed, and the normality and homoscedasticity of the distribution of residuals of models was visually verified.

The change in annual temperature (mean temperature, maximum temperature and minimum temperature) and total annual rainfall through time was tested using a Mann-Kendall trend test (R package “Kendall”, McLeod, 2011).

The evolution of SOC content (0–20 cm) through time was first tested using a Mann-Kendall trend test. In a second step, we used a linear mixed-effects model approach to explain the differences in SOC content across treatments for the period 1977–2016, with crop succession and soil tillage as fixed factors and sampling year as random factor following the R syntax: SOC ˜ crop succession × soil tillage + 1|year. Due to the low number of available SOC data, the effect soil tillage on SOC content during the period 1967–1976 could not be tested.

Concerning the 24 soil parameters measured in 2016 (Table 2), we used a linear mixed-effects model approach with crop succession, soil tillage and soil depth as fixed factors and block as random factor following the R syntax: Soil parameter ˜ crop succession × soil tillage × soil depth + 1|block. The full models were simplified to determine the most parsimonious models using the *stepAIC* function of the “MASS” package, an established model selection procedure with both forward and backward selection algorithms, which ranks all candidate models (all possible combinations of the initial explanatory variables included in the full model) based on lowest AICs (Crawley, 2007).

The effect of soil tillage on wheat yield was tested annually during the first period (1967–1976) and every second year during the period 1977–2016. For the period 1967–1976, we used a linear mixed-effects

Table 1

Summary of environmental conditions during the even years when winter wheat was cultivated in all treatments from 1978 to 2016. Environmental conditions were calculated for three periods according to the phenology of wheat: the vegetative period from sowing until heading (P1), the following 4 weeks period when flowering takes place (P2) and a last period until harvest when grain filling occurs (P3). Together they represent the full growing season (GS) from sowing date to harvest date. The different climate indices used are: (1) number of days of the GS, (2) mean, (3) minimum and (4) maximum temperature during the GS (°C), (5) total rainfall (mm), (6) growing degree days (GDD) until heading (base temperature equal to 0 °C), (7) number of days with daily maximum temperature above 25 °C, (8) number of days with daily minimum temperature equal or below 0 °C and (9) average solar radiation (MJ/m^2).

Variety	Year	Growing season (GS)						Period from sowing date to heading date (P1)						Period during 4 weeks after heading (P2)				Period from end P2 to harvest date (P3)			
		Sowing date	(1) Number of days	(2) Tmean ºC	(3) Tmin	(4) Tmax	(5) Rain mm	Heading date	(6) GDD	(7) T25 days	(8) T0	(5) Rain mm	(9) Ray MJ/m2	4 weeks after date	(7) T25 days	(5) Rain mm	(9) Ray MJ/m2	Harvest date	(7) T25 days	(5) Rain mm	(9) Ray MJ/m2
Zénith	1978**	11-Oct-77	306	8.3	(-1.2)	23.1	*> 745*	7-Jun-78	1513	2	*> 34*	*> 525*	*≈ 10.0*	5-Jul-78	1	75	16.5	12-Aug-78	14	145	17.0
	1980*	4-Oct-79	308	8.4	−9.1	32.0	972	9-Jun-80	1684	2	57	757	8.5	8-Jul-80	2	114	16.5	6-Aug-80	14	101	20.6
	1982*	7-Nov-81	264	8.5	−5.3	30.7	725	8-Jun-82	1375	5	59	546	10.3	6-Jul-82	6	146	18.1	28-Jul-82	13	34	19.1
	1984	30-Sep-83	315	8.2	−6.5	33.6	823	11-Jun-84	1526	0	79	772	9.4	8-Jul-84	9	21	23.1	9-Aug-84	18	30	21.2
	1986	16-Oct-85	293	8.0	−11.5	32.0	792	7-Jun-86	1337	2	88	683	8.1	4-Jul-86	19	41	24.5	4-Aug-86	16	68	22.4
	1988	20-Oct-87	287	9.3	−4.8	33.2	817	31-May-88	1592	1	46	691	8.0	27-Jun-88	4	24	21.4	1-Aug-88	17	103	21.1
	1990	9-Oct-89	290	9.4	−4.8	33.3	793	21-May-90	1651	1	59	581	8.4	18-Jun-90	1	105	18.6	25-Jul-90	22	107	22.8
	1992	11-Oct-91	281	7.9	−8.3	28.5	792	27-May-92	1414	5	77	555	9.1	24-Jun-92	3	139	17.3	17-Jul-92	7	99	20.9
Arina	1994	28-Oct-93	271	9.3	−7.3	32.0	729	1-Jun-94	1490	0	51	609	8.0	29-Jun-94	11	39	21.0	25-Jul-94	21	80	21.2
	1996	2-Oct-95	292	8.4	−7.4	29.9	660	26-May-96	1550	1	83	439	8.7	23-Jun-96	13	101	22.7	19-Jul-96	7	120	20.3
	1998	28-Oct-97	267	8.9	−5.3	34.5	603	27-May-98	1399	5	65	504	9.3	24-Jun-98	9	74	19.9	21-Jul-98	16	26	20.7
	2000	11-Oct-99	285	8.7	−11.6	32.6	779	25-May-00	1518	4	71	616	8.8	22-Jun-00	16	50	21.6	21-Jul-00	7	113	20.1
	2002	12-Oct-01	286	9.0	−9.4	33.7	607	2-Jun-02	1650	3	65	489	9.1	30-Jun-02	16	46	22.5	24-Jul-02	6	72	20.0
	2004	15-Oct-03	287	8.4	−10.5	31.4	693	29-May-04	1373	3	71	562	9.5	26-Jun-04	5	55	21.1	27-Jul-04	15	76	21.1
	2006	11-Oct-05	281	8.0	−9.4	30.9	694	28-May-06	1357	0	86	608	8.8	25-Jun-06	15	34	23.9	18-Jul-06	21	53	23.9
	2008	16-Oct-07	281	8.3	−6.3	30.7	681	27-May-08	1382	0	78	517	9.3	24-Jun-08	6	73	18.5	22-Jul-08	14	92	23.4
	2010	7-Oct-09	282	8.3	(-13.7)	34.3	653	27-May-10	1500	3	75	575	9.0	24-Jun-08	6	65	24.5	15-Jul-10	13	31	21.7
	2012	4-Sep-11	328	9.9	−13.2	33.4	830	25-May-12	2197	7	54	641	10.7	22-Jun-12	7	134	21.9	27-Jul-12	15	54	23.6
	2014	18-Nov-13	261	9.7	−4.2	30.4	765	29-May-14	1326	0	42	514	10.4	27-Jun-14	12	46	25.4	5-Aug-14	14	205	17.3
	2016	12-Oct-15	288	9.4	−6.3	32.7	861	27-May-16	1598	1	43	649	9.0	24-Jun-16	4	147	18.3	25-Jul-16	20	64	24.6
	mean	11-Oct	288	8.7	−7.8	31.6	751	27-May	1522	6	66	595	9.1	25-Jun	8	76	20.9	25-Jul	15	84	21.2
	min	4-Sep	261	7.9	−13.7	23.1	603	21-May	1326	0	42	439	8.0	18-Jun	1	21	16.5	15-Jul	6	26	17.0
	max	18-Nov	328	9.9	−1.2	34.5	972	11-Jun	2197	7	88	772	10.7	8-Jul	19	147	25.4	12-Aug	22	205	24.6

** Rainfall, solar radiation and minimum/maximum temperatures were not available for 1977, so the climatic conditions from sowing to heading was calculated with the data collected from 1 December 1978 (values in italics). */** Heading dates were not recorded during these years in this study, however, as approximation, heading dates of the same wheat variety in a nearby study within the same site were used.

Table 2
Mean soil properties in 2016 according to crop succession and soil tillage and at three soil depths (0–10, 10–20 and 20–50 cm). Values in brackets represent the standard error (n = 4).

Variable	Unit	Monoculture												Crop rotation											
		Plough						Minimum tillage						Plough						Minimum tillage					
		0–10 cm		10–20 cm		20–50 cm		0–10 cm		10–20 cm		20–50 cm		0–10 cm		10–20 cm		20–50 cm		0–10 cm		10–20 cm		20–50 cm	
Bulk density	g/cm^3	1.53	(0.05)	1.55	(0.02)	1.61	(0.02)	1.41	(0.03)	1.60	(0.02)	1.63	(0.05)	1.46	(0.01)	1.60	(0.02)	1.65	(0.03)	1.43	(0.01)	1.57	(0.01)	1.61	(0.03)
pH-water	H_2O	6.37	(0.20)	6.43	(0.24)	6.57	(0.23)	6.01	(0.09)	6.14	(0.12)	6.33	(0.13)	6.33	(0.13)	6.36	(0.12)	6.46	(0.11)	6.14	(0.04)	6.29	(0.06)	6.38	(0.03)
CEC	Cmol+/kg	12.2	(0.2)	12.1	(0.2)	11.7	(0.4)	12.0	(0.6)	12.3	(0.8)	11.3	(0.6)	11.9	(0.7)	12.0	(0.8)	11.5	(0.7)	11.5	(0.6)	11.7	(0.6)	11.4	(0.6)
SOC	g/kg	14.9	(0.3)	14.5	(0.4)	12.2	(0.5)	17.2	(0.6)	12.9	(0.6)	12.4	(0.6)	14.5	(0.6)	13.8	(0.6)	11.5	(0.6)	16.6	(0.5)	12.3	(0.5)	12.3	(0.5)
C:N	-	9.1	(0.1)	8.9	(0.1)	8.8	(0.3)	9.0	(0.1)	8.52	(0.1)	8.9	(0.1)	9.0	(0.2)	8.8	(0.1)	8.8	(0.1)	9.2	(0.1)	8.6	(0.2)	9.2	(0.3)
N_{tot}	g/kg	1.64	(0.04)	1.63	(0.03)	1.38	(0.07)	1.90	(0.08)	1.51	(0.08)	1.38	(0.06)	1.61	(0.07)	1.55	(0.06)	1.31	(0.08)	1.81	(0.06)	1.43	(0.08)	1.34	(0.08)
P_{tot}	g/kg	0.76	(0.02)	0.76	(0.03)	0.69	(0.04)	0.75	(0.02)	0.71	(0.02)	0.58	(0.02)	0.74	(0.03)	0.74	(0.03)	0.61	(0.03)	0.71	(0.03)	0.65	(0.04)	0.57	(0.04)
P_{min}	g/kg	0.42	(0.02)	0.42	(0.02)	0.36	(0.04)	0.40	(0.01)	0.39	(0.01)	0.29	(0.02)	0.41	(0.02)	0.41	(0.02)	0.33	(0.03)	0.37	(0.02)	0.34	(0.02)	0.28	(0.02)
P_{org}	g/kg	0.32	(0.01)	0.31	(0.01)	0.27	(0.01)	0.33	(0.01)	0.30	(0.01)	0.26	(0.01)	0.31	(0.01)	0.32	(0.01)	0.27	(0.01)	0.33	(0.01)	0.29	(0.01)	0.26	(0.01)
P_{NaHCO3}	mg/kg	19.2	(2.1)	20.7	(2.0)	16.7	(2.4)	20.4	(2.7)	19.3	(3.6)	13.3	(2.6)	18.4	(0.6)	19.4	(0.4)	14.8	(0.6)	15.5	(1.3)	13.0	(1.0)	9.8	(0.7)
K_{tot}	g/kg	18.3	(0.1)	17.9	(0.2)	17.6	(0.2)	17.5	(0.3)	18.4	(0.4)	17.5	(0.3)	17.8	(0.5)	18.1	(0.4)	16.9	(0.5)	17.3	(0.4)	17.8	(0.3)	17.2	(0.3)
K_{AA}	mg/kg	145	(7)	131	(8)	128	(14)	149	(8)	119	(8)	112	(8)	157	(7)	139	(7)	131	(9)	154	(12)	109	(10)	113	(5)
Ca_{tot}	g/kg	4.96	(0.34)	5.18	(0.43)	5.21	(0.55)	4.66	(0.24)	4.80	(0.20)	5.38	(0.28)	4.74	(0.19)	4.82	(0.25)	4.82	(0.11)	4.82	(0.03)	4.96	(0.15)	4.99	(0.08)
Ca_{AA}	g/kg	2.04	(0.12)	2.09	(0.11)	2.29	(0.17)	1.76	(0.13)	2.02	(0.15)	2.20	(0.18)	1.91	(0.14)	1.93	(0.13)	2.02	(0.13)	1.83	(0.12)	2.09	(0.20)	2.12	(0.16)
Mg_{tot}	g/kg	10.3	(0.1)	10.1	(0.2)	9.6	(0.2)	9.8	(0.4)	10.5	(0.5)	10.2	(0.6)	9.4	(0.6)	9.3	(0.7)	9.4	(0.7)	9.8	(0.4)	10.1	(0.5)	9.6	(0.4)
Mg_{AA}	mg/kg	120	(9.8)	115	(10.2)	118	(12.7)	139	(6.9)	118	(7.2)	129	(11.0)	122	(9.9)	117	(11.0)	116	(9.9)	141	(11.3)	114	(11.5)	127	(12.0)
Mn_{tot}	g/kg	0.88	(0.04)	0.87	(0.03)	0.83	(0.02)	0.86	(0.02)	0.87	(0.02)	0.84	(0.03)	0.81	(0.04)	0.83	(0.04)	0.77	(0.02)	0.87	(0.03)	0.89	(0.02)	0.83	(0.02)
Mn_{DTPA}	mg/kg	25.2	(2.3)	22.3	(1.6)	27.3	(2.6)	26.2	(2.3)	19.6	(0.6)	28.2	(1.2)	21.2	(1.6)	23.8	(1.5)	29.4	(1.3)	26.7	(0.8)	18.4	(0.9)	28.3	(1.6)
Zn_{tot}	mg/kg	73.1	(1.9)	71.4	(3.2)	68.1	(2.2)	70.4	(3.0)	71.9	(3.0)	69.3	(3.4)	68.0	(4.2)	67.7	(4.9)	67.6	(4.4)	68.9	(2.9)	71.0	(3.3)	68.4	(2.3)
Zn_{DTPA}	mg/kg	2.73	(1.01)	2.81	(0.98)	2.51	(0.78)	1.85	(0.16)	1.97	(0.56)	2.16	(0.62)	3.48	(0.89)	1.80	(0.15)	4.00	(2.51)	2.70	(0.73)	3.50	(0.58)	3.57	(0.96)
Cu_{tot}	mg/kg	34.6	(2.1)	33.7	(2.1)	30.6	(1.2)	30.6	(1.5)	31.5	(1.3)	29.0	(1.6)	30.8	(1.8)	29.9	(1.8)	28.2	(1.3)	29.6	(1.4)	30.5	(1.7)	27.9	(1.2)
Cu_{DTPA}	mg/kg	4.55	(0.65)	4.12	(0.58)	3.27	(0.39)	3.50	(0.32)	3.55	(0.11)	2.59	(0.10)	4.26	(0.59)	3.77	(0.51)	3.31	(0.47)	3.51	(0.25)	3.32	(0.27)	2.49	(0.20)
Fe_{tot}	g/kg	30.5	(0.9)	31.1	(1.0)	30.6	(1.0)	30.2	(1.5)	31.5	(1.3)	31.4	(1.9)	29.4	(1.9)	26.7	(1.7)	29.3	(1.6)	29.6	(1.0)	30.8	(1.4)	30.5	(0.9)
Fe_{DTPA}	mg/kg	91	(15)	88	(15)	71	(12)	104	(10)	93	(14)	71	(10)	96	(11)	91	(12)	72	(10)	93	(6)	74	(3)	63	(4)

model with soil tillage system as fixed factor and sampling year as random factor. For the period 1977–2016, we used a linear mixed-effects model with crop succession and soil tillage as fixed factors and sampling year as random factor. Finally, to assess to what extent the agricultural practices (including crop succession and soil tillage), the wheat phenology and the climatic conditions during key phenological stages of wheat (Table 1) influence wheat productivity, we used a multiple regression model following the formula: $Y_{yield} \sim X_{agricultural\ practices} + X_{phenology} + X_{climate}$. The full model was simplified to determine the most parsimonious models using the *stepAIC* function of the "MASS" package. To avoid collinearity affecting the model estimation, we ensured that correlation coefficients between variables were not higher than 0.7 (Dormann et al., 2013). Finally, the total explained variance of wheat productivity was separated into the partial variances of the selected explanatory variables.

3. Results

3.1. Overall climate

During the past 50 years, Mann-Kendall tests showed a significant increase of both the mean annual temperature (Fig. 1a) and the annual maximum temperature (Fig. 1d) in the study site. No significant trend was observed for the total annual rainfall (Fig. 1b) or the annual minimum temperature (Fig. 1c). Moreover, notable increases in temperature were observed from the 1980s onwards. In general, noteworthy year-to-year climatic variability was observed, revealing singular years, with for example extreme warm summers in 1976, 1986, 1994, 2003 and 2015 (Supplementary Fig. S1).

3.2. Wheat yield evolution

No specific trend for crop yield (neither increase nor decrease) was observed over time (tau = -0.0253, $P = 0.5849$; Fig. 2).

During the period 1967–1976, minimum tillage maintained a higher wheat yield compared to plough treatment (15% increase; $t = 4.36$, $P = 0.002$), with an average of 42.5 ± 2.4 dt ha^{-1} and 37.1 ± 2.14 dt ha^{-1} for minimum tillage and plough treatments, respectively.

In 1977, crop rotation was introduced. The average wheat yield during the period 1977–2016 ranged from 47.6 ± 1.5 for monoculture with minimum tillage to 55.3 ± 2.0 dt ha^{-1} for crop rotation with plough. Wheat yield was strongly affected by crop succession ($t = 6.30$, $P < 0.0001$; Fig. 3a), with a 16.2% increase of wheat yield in crop rotation compared to monoculture. On the other hand, minimum tillage showed no significant effect on wheat yield compared to the plough treatment during the period 1977–2016 ($t = 0.19$, $P = 0.8471$; Fig. 3b). Finally, no interaction was found between crop succession and tillage system ($t = -0.33$, $P = 0.7393$).

3.3. Soil organic carbon evolution

Across all treatments, the SOC content decreased over time (*tau* = -0.417, $P < 0.0001$; Fig. 4).

During the period 1977–2016, SOC content was on average 7% higher in minimum tillage compared to plough treatment ($t = 4.75$, $P < 0.0001$; Fig. 3d), while no significant main effect of crop succession ($t = -0.12$, $P = 0.2703$; Fig. 3c) or interaction between soil tillage and crop succession ($t = -1.48$, $P = 0.1498$) were observed. In 2016, an increase in SOC content was observed in the minimum tillage treatment compared to the plough treatment only in the 0–10 cm layer (significant soil tillage × depth interaction, Supplementary Table S1).

3.4. Effect of crop succession and soil tillage on soil properties in 2016

Crop succession, soil tillage and/or soil depth affected 17 of the 24 measured soil properties in 2016 (Tables 2 and 3; Supplementary Table S1) suggesting that minimum tillage caused a stronger stratification of soil properties compared to plough treatment.

Bulk density and pH increased according to soil depth while, as expected, the majority of nutrient concentrations, except Mn_{DTPA}, decreased according to soil depth (Table 3). The combination of crop rotation and minimum tillage showed lower bulk density compared to monoculture and plough treatments, respectively (Table 3). Except for Mn_{tot}, the concentrations of N_{tot}, P_{tot}, P_{min}, K_{tot}, Mg_{tot} and Cu_{tot} were lower in crop rotation compared to monoculture (Table 3). Minimum tillage treatment showed a slight soil acidification compared to plough treatment (Table 3). N_{tot} content was higher in minimum tillage compared to plough treatment until 20 cm soil depth (significant tillage × depth interaction, Supplementary Table S1) while, on the other hand, the concentrations of P_{tot}, P_{min}, K_{tot}, Cu_{DTPA} and Mn_{DTPA} were lower in minimum tillage compared to the plough treatment (Table 3).

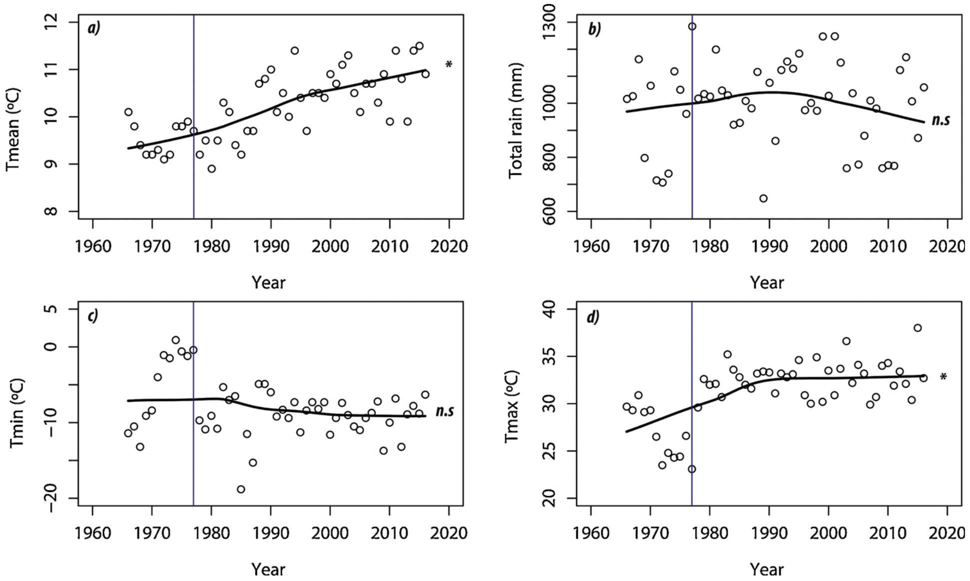

Fig. 1. Temporal evolution of annual climate during the period 1967–2016 in Changins, Switzerland. Asterisks ($P < 0.05$) and n.s ($P > 0.05$) indicate the significance of temporal trends according to Mann-Kendall tests. The blue vertical line corresponds to the year 1977 when the crop rotation was introduced in the experiment.

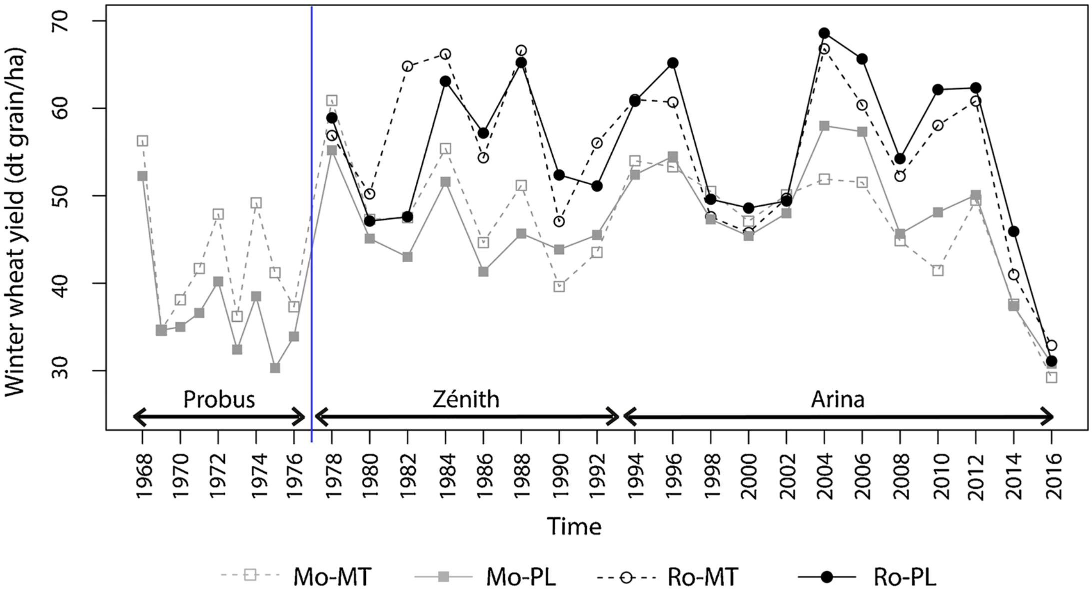

Fig. 2. Temporal evolution of wheat yield during the period 1967–2016. Mo-MT = monoculture with minimum tillage, Mo-PL = monoculture with plough, Ro-MT = crop rotation with minimum tillage, Ro-PL = crop rotation with plough. Three winter wheat varieties were used during the study period: Probus (1967–1976), Zénith (1977–1992) and Arina (1993–2016). The blue vertical line corresponds to the year 1977 when crop rotation was introduced in the experiment.

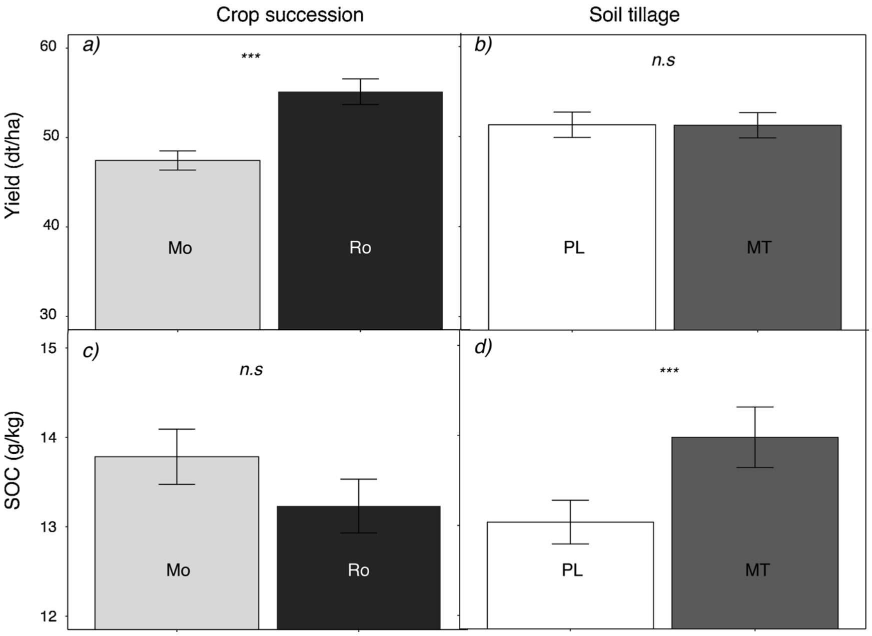

Fig. 3. Mean effect of crop succession (a, c) and soil tillage (b, d) on wheat yield (a, b) and soil organic carbon content (c, d) during the period 1977–2016. Each bar represents the mean value ± SE; n = 24. Asterisks ($P < 0.001$) and n.s ($P > 0.05$) indicate the significance of treatments. Mo = monoculture, Ro = crop rotation, PL = plough, MT = minimum tillage, SOC = soil organic carbon.

3.5. Agricultural practices, climate and wheat phenology as explanatory variables of wheat yield

The climatic conditions for wheat during the growing season over the period 1977–2016 are reported in Table 1. The multiple linear regression model revealed that the number of days below 0 °C prior to heading ($t = 4.55$, $P < 0.0001$), the number of days above 25 °C ($t = -3.31$, $P < 0.001$) and the accumulated rainfall during the month after heading ($t = -5.08$, $P < 0.0001$) explained the wheat yield variability observed in the past 39 years (1977–2016). Increased number of warm days and of days with heavy rain reduced wheat yield, while more cold days prior to heading and increased growing degree days improved wheat yield. Regarding phenological factors, the number of growing degree days also explained wheat yield variability ($t = 3.00$, $P = 0.003$). Among the agricultural practices, only crop succession showed an important positive effect on wheat yield ($t = 5.27$, $P < 0.0001$). The resulting model showed that, during the period 1977–2016, 45.5% of yield variability can be explained by the selected explanatory variables related to crop management, wheat phenology and climatic conditions. More specifically, the climatic conditions around the heading phase explained 21.9% of the variance of wheat yield, while 17.8% was explained by crop succession and 5.8% by the growing degree days prior to heading stage.

4. Discussion

4.1. Effects of crop succession and soil tillage on wheat yield

During the period 1977–2016, wheat in crop rotation had 16% higher productivity compared to monoculture, which is in agreement with results from previous studies (Berzsenyi et al., 2000; FAO, 2011; Helmers et al., 2001; Kirkegaard et al., 2008). Improvements in water

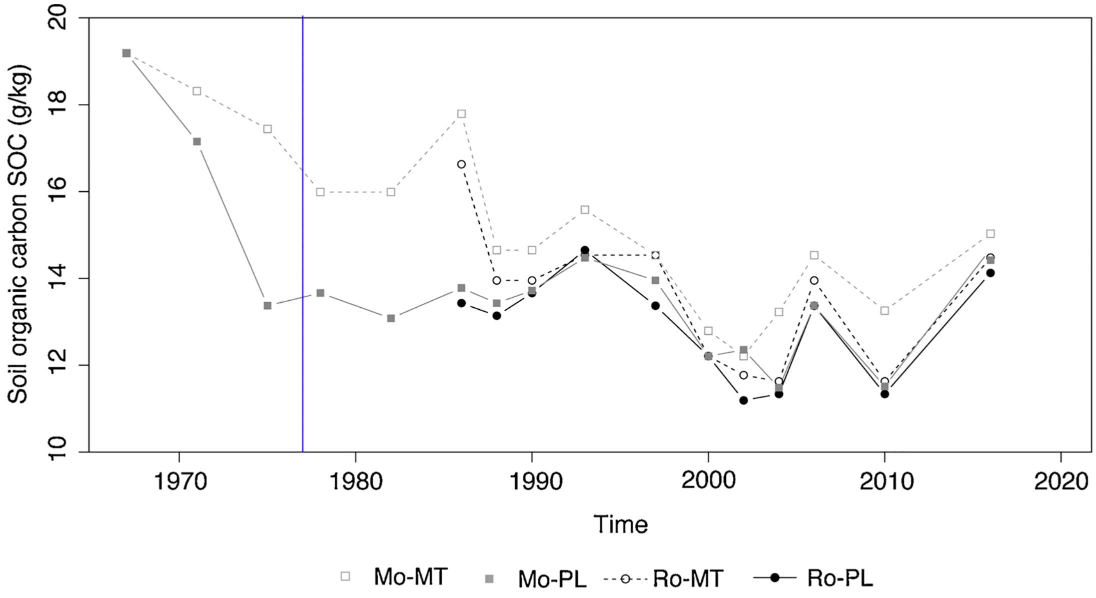

Fig. 4. Temporal evolution of soil organic carbon content (0–20 cm depth) during the period 1967–2016. Mo-MT = monoculture with minimum tillage, Mo-PL = monoculture with plough, Ro-MT = crop rotation with minimum tillage, Ro-PL = crop rotation with plough. The blue vertical line corresponds to the year 1977 when crop rotation was introduced in the experiment.

Table 3
Synthesis of the effects of i) crop rotation compared to monoculture, ii) minimum tillage compared to plough and iii) soil depth increase on the 24 soil properties measured in 2016. ↘ indicates a significant decrease of the value, ↗ indicates a significant increase of the value and the absence of arrow indicates the absence of a significant effect (Supplementary Table S1).

	Crop rotation *vs* monoculture	Minimum tillage *vs* plough	Increasing depth
Bulk density	↘	↘	↗
pH-water		↘	↗
CEC			
SOC		↗	↘
C:N		↘	
N_{tot}	↘	↗	↘
P_{tot}	↘	↘	↘
P_{min}	↘	↘	↘
P_{org}			↘
P_{NaHCO3}			↘
K_{tot}	↘	↘	↘
K_{AA}			↘
Ca_{tot}			
Ca_{AA}	↘		↗
Mg_{tot}	↘		
Mg_{AA}			
Cu_{tot}	↘		↘
Cu_{DTPA}		↘	↘
Fe_{tot}			
Fe_{DTPA}			↘
Mn_{tot}	↗		↘
Mn_{DTPA}		↘	↘ ↗
Zn_{tot}			
Zn_{DTPA}			

(FAO, 2011) and soil nutrient availability (Gan et al., 2015; Tiemann et al., 2015), in soil structure (FAO, 2011; Hobbs et al., 2008) and in soil microbial activity (Hobbs et al., 2008; Mbuthia et al., 2015; McDaniel et al., 2014) or the decrease in insect pressure and disease incidence (Berzsenyi et al., 2000; FAO, 2011; Kirkegaard et al., 2008) could be responsible for this crop yield increase in crop rotation. Vullioud (2007) also reported that winter wheat in monoculture exhibited higher risks of diseases compared to crop rotation. In fact, crop rotation presents an advantage over monoculture as it breaks the life cycle of pathogens and pests, and interrupts the infection chain between subsequent crops (FAO, 2015; Kirkegaard et al., 2008).

At the beginning of the experiment, we observed a strong yield decline in both soil tillage treatments. Vullioud (2007) suggested that this decline could be due to the low resistance of the variety Probus against lodging. In the present study, a natural meadow with 19.2 g kg^{-1} SOC was converted to a wheat monoculture in 1967. The introduction of soil tillage induced an increased mineralisation of the soil organic matter (SOM) leading to an important carbon loss, as shown by Ding et al. (2013); Mbuthia et al. (2015) and Oberholzer et al. (2014), and an increase in soil N availability. High amounts of available soil N have probably induced wheat lodging and reduced the harvested yield.

During the period 1967–1976, the SOC decline was less dramatic in the minimum tillage compared to the plough treatment. Therefore, wheat lodging and yield decline (-25%) were lower in the minimum tillage compared to the plough treatment (-33%). As the starting point was quite different (natural meadow *vs.* already ploughed arable land), our results are not contradictory with previous studies that reported a yield decline when conventional tillage is converted to conservation tillage (Pittelkow et al., 2015b; So et al., 2009). In our study, the great soil disturbance caused by plough has negatively affected wheat yield in the short-term.

The substantial increase of yield in 1977 was mainly due to a change in wheat variety, with a higher productivity and resistance to eye spot (*Cercosporella herpotrichoides*) of Zénith and Arina compared to Probus (Vullioud, 2007). The initial positive effect of reduced tillage disappeared during the period 1977–2016 when new varieties, less susceptible to lodging, have been cultivated and once the soil system has reached a new equilibrium after the land use change. In addition, the retention of crop residues and the use of herbicides for weed control could have also mitigated the negative effects of minimum tillage on crop yield as reported in other studies (Erenstein et al., 2012). These findings are in agreement with previous studies that reported similar long-term yields between conventional and conservation tillage systems (Büchi et al., 2017; Pittelkow et al., 2015b).

4.2. *Effects of crop succession and soil tillage on soil organic carbon content and other soil properties*

Overall, SOC content was reduced by approximately 24% over the period 1967–2016, from 19.2 g kg^{-1} to 14.6 g kg^{-1}. However, despite a strong decline during the first ten years of study (1967–1976), SOC content remained more stable during the period 1977–2016. This leads to the hypothesis that SOC content was largely affected by a change in land use, from natural meadow to cropland (Maltas et al., 2018; Mbuthia et al., 2015). Another long-term field experiment in Zurich-Reckenholz (Switzerland) showed that the conversion from grassland to cropland caused a sharp decline in SOC when only mineral fertilizers have been applied (Oberholzer et al., 2014).

Variations in SOC content observed between sampling years, particularly from 2000, could be explained by the spatial heterogeneity and differences in soil temperature and moisture during the weeks preceding soil sampling. Nevertheless, we observed a significant effect of soil tillage on SOC content during the period 1977–2016, with 7% higher SOC content in the minimum tillage compared to the plough treatment, highlighting that reduced tillage allows a greater SOC content over a long-term period. This important finding is in agreement with previous studies that also reported an increased SOC content in crops cultivated with conservation tillage practices (including zero tillage and minimum tillage) compared to conventional ploughed systems (Hobbs et al., 2008; Mbuthia et al., 2015; Sauvadet et al., 2018; Song et al., 2016; Büchi et al., 2017). In fact, a higher mineralisation rate and higher C losses are generally observed in conventional tillage compared to conservation tillage (Six et al., 2002). Indeed ploughing destroys soil aggregates that serve as a physical protection of soil C (Maltas et al., 2013; Song et al., 2016). Thus, the use of minimum tillage increases the SOC content in the soil which is of paramount importance for both soil fertility and climate change mitigation.

Surprisingly, while crop rotation increased crop yield compared to monoculture, we observed no significant effect of crop succession on SOC content during the period 1977–2016. SOC content even tended to be lower in crop rotation compared to wheat monoculture. Regarding the impact of crop succession on SOC content, some previous studies showed that crop diversification increases SOC content compared to monoculture (Tiemann et al., 2015; McDaniel et al., 2014), while other studies showed no effect of crop succession system on SOC content (Snapp et al., 2010; Soon et al., 2007). In the present study, the absence of crop succession effect on SOC content could be explained by a higher organic carbon mineralisation (Lupwayi et al., 1998; Roper et al., 2012) which cancels higher crop biomass inputs in crop rotation compared to monoculture.

Concerning the other soil properties measured in 2016, in line with previous studies (Büchi et al., 2017; Melero et al., 2012; Zhang et al., 2015), a strong stratification pattern with depth were observed for 15 of the 24 analyzed soil properties. Minimum tillage induced a greater stratification of these soil properties than plough. Both minimum tillage and crop rotation showed lower bulk density compared to plough and monoculture systems, respectively, highlighting a reduction in soil compaction and preventing soil erosion and water runoff at the same time (Mbuthia et al., 2015; McDaniel et al., 2014; Six et al., 2002; Tiemann et al., 2015). The concentrations of seven nutrients (N_{tot}, P_{tot}, P_{min}, K_{tot}, Ca_{AA}, Mgt_{ot}, Cu_{tot}) were lower in crop rotation compared to monoculture, while the concentrations of five nutrients (P_{tot}, P_{min}, K_{tot}, Cu_{DTPA}, Mn_{DTPA}) were lower in the minimum tillage compared to plough. As nutrient inputs were identical in all treatments, the negative effect of crop rotation on some soil nutrients can be explained by higher nutrient export due to higher plant biomass compared to monoculture.

4.3. *Climate as explanatory variable for wheat yield variability*

According to Ray et al. (2015) a third of the global crop yield variability could be explained by climatic variation. However, climate impact on crop yield needs to be assessed in combination with other factors such as agricultural practices and crop physiology.

Overall, our results show that the stage of heading was highly sensitive to changing climatic conditions. These findings are in agreement with other studies that stated that extreme climatic conditions can be critical when occurring during key stages of crop development (Gornall et al., 2010; Holzkämper et al., 2014; Wheeler et al., 2000). A detailed spatio-temporal analysis of climatic yield potentials of winter wheat in Switzerland showed that production of this crop was limited mostly by excess of water, frost and heat stress (Holzkämper et al., 2014). In 2016, the heavy rains and low radiation occurring in our study site after the heading stage led to an average drop of wheat yield in monoculture of 23.8% compared to the mean yield of the previous five years. Similar results were reported in France (Colart et al., 2016). Two possible reasons could explain this yield decline: an excess of water during the flowering stage that negatively impacts the spike fertility (Colart et al., 2016) and heavy rains during wheat development that enhance *Septoria tritici* infection (Thomas et al., 1989). Therefore, wheat yield is influenced by a combination of factors which include the characteristics of the variety (*e.g.* biotic resistance or phenology), the applied agricultural practices and the climatic conditions during critical stages of wheat development. We can conclude that climatic variables measured during the different growth development stages are more accurate in explaining yield variability than averaging these variables over the entire growing season.

5. Conclusion

Our long-term experiment shows that crop rotation increased wheat yield by 16% compared to monoculture. Beneficial effects of reduced tillage have been highlighted: i) increase in wheat yield over a short-term period, ii) same crop yield as in a conventional plough over a long-term period, and iii) higher SOC content compared to conventional plough. Thus, our long-term field experiment points out the beneficial effects of reduced tillage that, in addition to preserving both soil fertility and biological activity, could increase wheat yield over a short-term period and exhibit a comparable yield over a long-term period as in conventional plough. Finally, our study also demonstrated that the variation of climatic conditions over the 50-year period explained a higher proportion of wheat yield variability compared to agricultural practices, highlighting the need to also consider this key parameter to predict crop productivity.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2019.01.012.

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