Field Crops Research 255 (2020) 107871

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Cover crops during transition to no-till maintain yield and enhance soil fertility in intensive agro-ecosystems

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ARTICLE INFO

Keywords:
soil organic matter
soil total nitrogen
crop yield
winter cover crops
no-till

ABSTRACT

Introducing no-till and cover crops in arable agro-ecosystems leads to the restoration of soil fertility, through the increase of soil organic matter (SOM), soil total nitrogen (STN), and available phosphorus (P), therefore maintaining or enhancing crop yield and reducing costs. Although the effects of those practices have been widely examined, many studies show conflicting results and little is known about the combined effects of no-till (NT) and cover crops (CCs) under intensive arable cropland in the Po Valley (Northern Italy). The objectives of this study were: (i) to evaluate if NT management coupled with CCs negatively affects yields during the transition period and how yields evolve; (ii) to assess SOM, STN, and P dynamics in the 60-cm soil depth layer; and (iii) to evaluate the effects of different types of winter cover crops on yield and soil parameters.

A six-year field experiment was established in Piacenza, on a silty-clay soil under temperate climate conditions. The crop sequence was: winter wheat, maize, maize, soybean, winter wheat, and maize. The four experimental treatments were: (1) conventional tillage (CT) as control; (2) NT with CC of rye (NT-R); (3) NT with CC of hairy vetch (NT-V); and (4) NT with a mixture of CCs (rye, hairy vetch, crimson clover, Italian rye-grass and radish) [NT-M]). Dry biomass yield of CCs ranged between 2.2 and 3.1 Mg ha^{-1} for rye; 1.9 and 3.0 Mg ha^{-1} for hairy vetch; and 1.9 and 3.2 Mg ha^{-1} for mixture. In the present study, yields of winter wheat, maize, and soybean were generally not reduced with NT-CCs since the first year after conversion. The different composition and thickness of cover crop mulch showed an opposite yield response to rainfall pattern: under NT-R, a negative correlation was observed between grain yield and rainfall, while under NT-V this correlation was positive.

After six years, SOM and STN concentrations in the 0-30 cm soil layer increased in NT-CCs. SOM concentration was +30%, +23% and +20% higher than CT for NT-R, NT-M and NT-V, respectively. STN was +28% higher under NT-R and NT-V, and +21% higher under NT-M, than CT. Conversely, P concentration was not influenced by the NT-CCs system, although we observed a tendency to increase under NT-V. In the 30-60 cm soil, layer, the tillage systems did not affect SOM and STN.

We concluded that introducing NT with winter CCs into intensive arable agricultural systems is an effective strategy for enhancing soil fertility in fine-textured soils under temperate climates, without penalizing yields.

1. Introduction

Variations in soil-crop management of agro-ecosystems highly impact the status of soil fertility (Paustian et al., 1997) and may affect, either positively or negatively, the provision of multiple ecosystem services (Stavi et al., 2016; Ferrarini et al., 2018). Conventional intensive tillage operations promote soil organic matter (SOM) mineralization and soil organic carbon (SOC) loss to the atmosphere as carbon dioxide (CO_2) (Lal, 2011), thus negatively impacting climate change (Mangalassery et al., 2014). Therefore, introducing sustainable soil-crop management of agro-ecosystems that can sequester additional CO_2 as SOC is a major requirement for building resilience to climate change (Lal, 2016). Yet, these management systems (i.e. no-till [NT]) may sometimes reduce crop yield due to unfavorable soil-climate conditions, insufficient knowledge, or lack of appropriate technical assistance and machinery during the transition period (Derpsch et al., 2014).

A number of findings from long-term field studies and meta-analyses indicate that the response of SOM concentration to NT management is highly related to soil type, climate, cropping strategies, and

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https://doi.org/10.1016/j.fcr.2020.107871
Received 21 January 2020; Received in revised form 27 May 2020; Accepted 31 May 2020
Available online 15 June 2020
0378-4290/

experiment duration (West and Post, 2002; He et al., 2011; Derpsch et al., 2014). Positive effects of NT were reported mainly in the long-term, in hot and dry climates, and when combined with cover crops (Kassam et al., 2012). In addition, it was reported that NT often results in SOM redistribution along the soil profile rather than in a net SOM increase (Luo et al., 2010). Specifically, Powlson et al. (2014) found that the effect of NT on increasing SOM in the surface soil layers compared with conventional tillage (CT) systems is sometimes offset by greater SOM content near the bottom of the plow layer under CT. Similarly, for available phosphorus (P) many studies reported clear evidence of stratification under NT (Deubel et al; 2011; He et al., 2011; Obour et al., 2017).

As for SOM, responses of crop yield to NT, compared with CT, are often contradictory and vary widely according to crop, climate, and soil conditions, especially during the transition period. For instance, Pittelkow et al. (2015), in a recent global meta-analysis, found that yield performance depends on the field crop under consideration. These authors reported that NT tends to constantly decrease the yield of maize, rice, and root crops even in the long-term (> 5 years). Conversely, in the Po Valley (Northern Italy) it was found that the grain yield of irrigated maize under NT could be equal to, or even slightly higher than, the yield obtained under CT (Tabaglio and Gavazzi, 2006). As regards winter cereals (i.e. wheat, barley, and oat), a yield reduction under NT compared with CT generally occurs in the initial 1-3 transition years (Pittelkow et al., 2015). However, to further complicate matters, climate and soil types may affect this response: Ogle et al (2012) observed that adopting NT reduces crop yields mainly in cold and wet continental climates, even in the long-term. Conversely, many researchers in Italy and abroad found better yield performances for winter cereals in NT soils starting from the first year of conversion, under dry Mediterranean climate and rain-fed conditions (Cantero-Martínez et al., 2003; De Vita et al., 2007; Lampurlanés et al., 2016). Last but not least, Mazzoncini et al. (2008) reported that on poorly drained silty-loam soils NT may reduce the yield of wheat by 10%.

Introducing CCs together with NT was suggested to mitigate the unfavorable effects of transition and consequent yield reduction (Fageria et al., 2005; Alvarez et al., 2017), as well as to further increase positive effects on SOM, STN, and P concentrations (Blanco-Canqui et al., 2011). The SOM enrichment deriving from cover crops cultivation is related to biomass input, which is greatly influenced by cover crop species, climate, and soil type (Ding et al., 2006). For instance, Villamil et al. (2006) found a SOM increase between 2.5 and 3.8 g kg^{-1}, compared to bare fallow, after only two years of NT and cover crops in a silty-loam soil under a corn-soybean rotation. Pittelkow et al. (2015), in their meta-analysis, show better yield response to NT when coupled with CCs. Adoption of NT and CCs has been recently promoted by the Common Agricultural Policy of the European Union throughout the Rural Development Programmes of the Regions in the Po Valley (2014-2020). However, few studies were conducted to assess the effect of NT on crop yield and on soil fertility under these soil-climate conditions and mainly in the short-term. Earlier results in the long-term derive from field experiments conducted in Central and Southern Italy, under different soil-climate conditions. In addition, none of them included the cultivation of cover crops (CCs).

In our six-year study we explored the implications of combining NT and CC cultivation in comparison with CT practices, assessing the effects on crop yield and on selected soil quality parameters (i.e. SOM, STN, and P) during the transition period in irrigated silty-clay soil under temperate climate conditions. Our hypotheses were: (i) when NT is coupled with winter CCs, there is no reduction in crop yield during the transition period; (ii) SOM, STN, and available P concentration are improved when NT is coupled with CCs; and (iii) the effect on yield and soil fertility varies depending on the different types of cover crops.

Table 1
Soil physical and chemical properties (0-30 and 30-60 cm soil depth) at the beginning of the experiment (2011).

Soil property	Unit	0-30 cm	30-60 cm
Sand (2 – 0.05 mm)	g kg^{-1}	122	399
Silt (0.05 – 0.002 mm)	g kg^{-1}	462	472
Clay (< 0.002 mm)	g kg^{-1}	416	129
pH (H_20)		6.8	7.0
pH ($CaCl_2$)		5.6	5.4
$CaCO_3$ (volumetric)	g kg^{-1}	2.5	1.0
Organic Matter (Walkley and Black)	g kg^{-1}	23	21
Total N (Kjeldahl)	g kg^{-1}	1.2	1.1
C:N ratio		11.1	11.1
Available P (Na bicarbonate 0.5 M, pH 8.5)	mg kg^{-1}	32	25
Exchangeable K (Ba chloride, pH 8.1)	mg kg^{-1}	294	257
C.E.C. (Ba chloride, pH 8.1)	$cmol^{+}$ kg^{-1}	30	30

2. Materials and methods

2.1. Site description

A six-year field experiment was carried out at CERZOO, the research farm of Università Cattolica del Sacro Cuore, near Piacenza (45°00'18.0" N, 9°42'12.7" E; 68 m above sea level), Po Valley, Northern Italy. The soil is a fine, mixed, mesic Udertic Haplustalfs (Soil Survey Staff, 2014). Main physical-chemical properties of the soil are summarized in Table 1. The site is characterized by a temperate climate, with an average annual temperature of 14.2 °C and annual rainfall of 778 mm (20-year average). Climatic data were collected from an automated meteorological station placed in the experimental field (Fig. 1).

2.2. Experiment and treatments

The field experiment was established in 2011 to compare contrasting tillage systems: (i) conventional tillage (CT), consisting of moldboard ploughing to 30-cm depth with residue incorporation, followed by two rotary harrowing to 15-cm depth for seedbed preparation, and (ii) no-till (NT), consisting of direct sowing on untilled soil with residue maintained on the soil surface. During off seasons, cover crops (CCs) were sown in NT plots after harvesting the previous main crops. The experiment was designed as a Randomized Complete Block (RCB) with four replicates and four treatments. Each plot was 22 m wide and 65 m long (1430 m^2). The four treatments were: (1) CT; (2) NT-R: NT with rye (*Secale cereale* L.) as CC; (3) NT-V: NT with hairy vetch (*Vicia villosa* Roth.) as CC; and (4) NT-M: NT with a mixture as CC [rye 55%; hairy vetch 25%; crimson clover (*Trifolium incarnatum* L.) 8%; Italian rye-grass (*Lolium multiflorum* Lam.) 8%; and radish (*Raphanus sativus* L.) 4%]. The seeding rate of CCs were 110 kg ha^{-1} for rye, 80 kg ha^{-1} for hairy vetch, and 60 kg ha^{-1} for mixture. Approximately two weeks before sowing the main crop, CCs were terminated by spraying Glyphosate [N-(phosphonomethyl) glycine] at the rate of 3 L ha^{-1}. Crop rotation during the six-year experiment was: winter wheat - maize - maize – soybean – winter wheat - maize. All plots were tilled conventionally before starting the experiment. A summary of crop managements is reported in Table 2. Neither P nor K fertilizers were applied.

Both maize and soybean were irrigated by traveling sprinkler, while winter wheat was cropped under rainfed conditions. The volume of irrigation-water was estimated from the crop's evapotranspiration (ET_c) of the previous week (net water requirements) as follows: $ET_c = K_c \times ET_0$, where ET_0 is the reference evapotranspiration calculated by the FAO Penman-Monteith method, while K_c is the crop coefficient calculated for each crop under our climatic conditions. The crop irrigation requirements (CIR) were determined weekly as the difference between the ET_c and the actual precipitation.

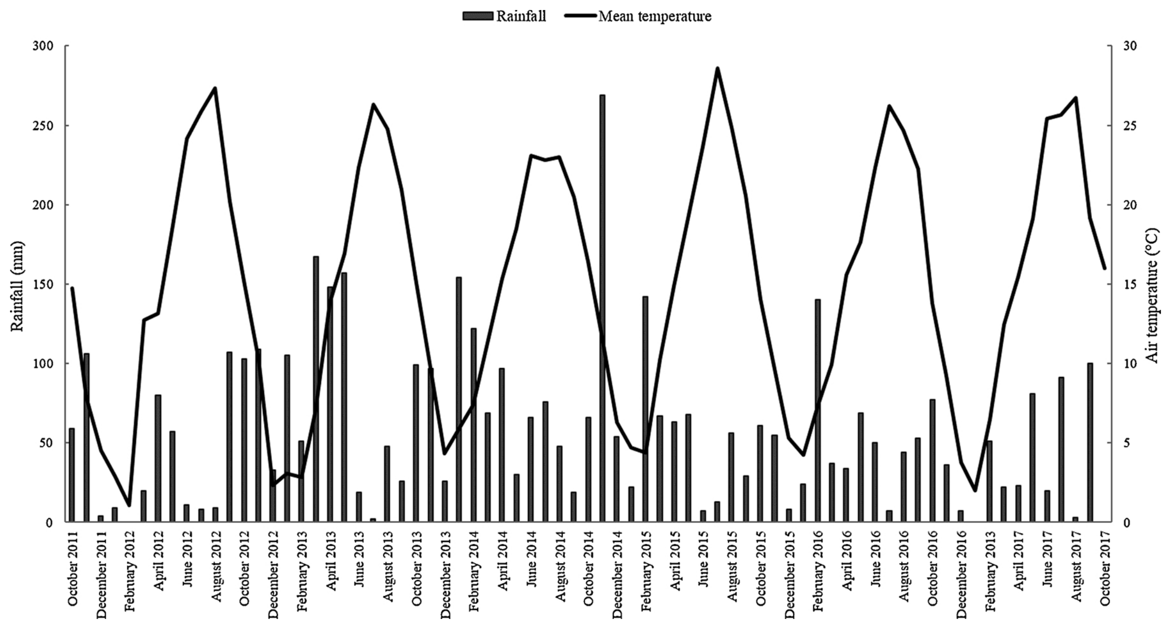

Fig. 1. Monthly rainfall (columns) and air temperature (line) at the experimental site from October 2011 to October 2017.

2.3. Yield measurements

Yield components (grain, straw/stover and total biomass) were determined annually by manually harvesting three representative areas of 6 m^2 per plot. Plants were separated into spikes and stems plus leaves for mass determination. Grain yield was calculated by separating the grain from the spikes using a mechanical thresher. Dry matter yields were obtained by oven-drying sub-samples at 105 °C until constant weight. Soybean straw was measured at maturity, also collecting fallen leaves. For each crop, harvest index (HI) was calculated as the ratio of grain yield to the total biomass at harvest on a dry matter basis. Total nitrogen (N) uptake was calculated by multiplying grain and straw/stover dry matter by their respective N concentrations, which were determined by Kjeldahl method (Bremner and Mulvaney, 1982). Plant height was assessed at harvest by measuring plant size from the ground level directly in the sampling areas; plant and spike density was calculated by counting the number of plants and spikes in collected samples.

Total aboveground biomass of cover crops was determined by harvesting plants from three areas of 3 m^2 each, randomly chosen within each plot and weighed in the field. For each sample, a sub-sample was collected to determine dry matter content, after oven drying at 105 °C, and then N concentration, by Kjeldahl method, after grinding at 2 mm size. N uptake was calculated by multiplying dry matter by its N concentration. For 2013-2014, data on CCs are not available due to a severe slug attack during plant emergence.

2.4. Soil sampling and analysis

Soil samples were collected in October 2017 after harvesting maize. Three composite soil cores were collected randomly from each plot at a 60 cm depth. Each soil core was then divided into five depth sections, respectively: 0-5, 5-15, 15-30, 30-45, and 45-60 cm. Soil samples were air-dried, ground and sieved (2 mm mesh) before determination of soil organic matter (Nelson and Sommers, 1982), soil total N (Bremner and Mulvaney, 1982), and available P (Olsen and Sommers, 1982).

2.5. Statistical analysis

Analysis of variance (ANOVA) was conducted using the “agricolae” package of RStudio 3.3.3. All variables were examined for normality with Shapiro-Wilk test and for homogeneity of variances with Levene’s test. When the tests did not confirm the assumptions of ANOVA, data were log-transformed before analysis. The means of each of the four treatments (CT, NT-R, NT-V, and NT-M) were compared using Tukey’s test ($P < 0.05$) (“multcomp” package).

Multivariate correlation analysis was performed to assess the relationship between grain yield and precipitation and irrigation patterns, using the non-parametric Spearman rank coefficient (ρ). A p value of 0.05 was considered significant for the test. Because of the diversity of crops, grain yields for each crop were normalized using *Z score*, which was calculated as follows:

$$z = \frac{x - \mu}{\sigma}$$

where x is each data point, μ is average yield production for every year, and σ is standard deviation.

3. Results

3.1. Environmental and meteorological conditions

The rainfall pattern during the experimental period (2011-2017, Fig. 1) differed considerably from the long-term (1991-2010) mean pattern (Table A1). Except for 2013 and 2014, annual rainfall was lower than the 20-year average. In detail, from October 2011 to June 2012 cumulative rainfall recorded at the field experiment was 260 mm, lower by 43% than the 20-year average value. In 2013, spring was characterized by abundant precipitations (472 mm in the March-May period), which caused a maize planting delay of more than one month. In 2014, annual rainfall was about 300 mm higher than the long-term mean, but with a shortage of 50 mm during the growing season. In 2015, 2016, and 2017, annual rainfall was more than 25% lower than the 20-year average. From April to September 2015, the rain shortage was about 38%; from October 2015 to June 2016, rainfall was 21% lower than the average and in 2017, rainfall during maize growing season was 65 mm lower than the long-term average for the same period.

Table 2
Crop sequence and management during the field experiment (2011–2017)

Year	Crop	Crop sowing	Seeding rate/ plant density	Fertilization	Weed and pest control	Harvest	CCs sowing	CCs termination
2011–2012	**Winter wheat Hy. Hyxo**	18/10/2011	60 kg ha^{-1}	94 Kg N ha^{-1} (stem elong.) 51 kg N ha^{-1} (heading)	3 L ha^{-1} Ariane II, (Fluroxipir 3.6%; Clopiralid 1.8%; MCPA 18.2%)	05/07/2012	20/10/2012	25/04/2013
2012–2013	**Maize Hy. P1114 FAO 500**	08/06/2013	7.8 seeds m^{-2}	100 kg N ha^{-1} (V2-V3) 100 kg N ha^{-1} (V8-V9)	1.2 L ha^{-1} Ghibli (Nicosulfuron 4.2%) + 1.3 L ha^{-1} Calaris (Terbuthylazine 29.3%; Mesotrione 6.2%).	17/10/2013	21/10/2013	Slug attack during CCs emergence
2013–2014	**Maize Hy. SNH 9609 FAO 600**	18/04/2014	7.8 seeds m^{-2}	100 kg N ha^{-1} N (V2-V3) 150 kg N ha^{-1} N (V8-V9)	1.2 L ha^{-1} Ghibli (Nicosulfuron 4.2%) + 1.3 L ha^{-1} Calaris (Terbuthylazine 29.3%; Mesotrione 6.2%)	17/09/2014	20/10/2014	21/04/2015
2014–2015	**Soybean cv. Bahia FAO 1-**	08/05/2015	40 seeds m^{-2}	–	2 L ha^{-1} Stratos (Cicloxidim 21%) +5 g ha^{-1} Harmony (Tifensulfuron-methyl 75%)	01/10/2015	–	–
2015–2016	**Winter wheat cv. Monastir**	13/11/2015	240 kg ha^{-1}	64 kg N ha^{-1} (tillering) 108 kg N ha^{-1} (stem elong.)	270 g ha^{-1} Floramix (Cloquintocet-Mexil 70.8%; Florasulam 14.2%, Pyroxsulam 70.8%).	08/07/2016	12/10/2016	07/04/2017
2016–2017	**Maize Hy. P36B08 FAO 300**	24/04/2017	7.8 seeds m^{-2}	80 kg N ha^{-1} (V3) 120 kg N ha^{-1} (V6)	1.2 L ha^{-1} Ghibli (Nicosulfuron 4.2%) + 1.3 L ha^{-1} Calaris (Terbuthylazine 29.3%; Mesotrione 6.2%)	24/09/2017	–	–

3.2. Yield, N uptake, and other yield components of winter wheat, maize, and soybean

Under NT-CCs, grain yield and straw yield, as well as the total biomass production and the HI of winter wheat (Table 3) were comparable to those observed under CT, in 2012. Conversely, NT-CCs affected plant height, which was 5% higher under NT-V than under CT (Table 4). In 2016 instead, wheat grain yields under NT-M (6.42 Mg ha^{-1}) and NT-R (6.32 Mg ha^{-1}) were significantly lower than those observed under CT (7.58 Mg ha^{-1}) and under NT-V (7.48 Mg ha^{-1}), affecting negatively the total N uptake, which was significantly higher for NT-V and CT than for NT-R (Table 3). No differences in plant density and spike density were detected among treatments, both in 2012 and in 2016 (Table 4).

Grain yield, stover yield and total biomass of maize, as well as HI and total N uptake, did not show any difference among CT and NT-CCs in all the years under consideration (2013, 2014, and 2017)(Table 3).

Different treatments did not affect plant height of maize in 2013 and 2017, while in 2014 plant height under all NT-CCs was 4% lower than that under CT (Table 4). Plant and spike density of maize were comparable among CT and NT-CCs in all the years (2013, 2014, and 2017).

Grain yield of soybean was negatively affected by NT-V, which showed the lowest production (-3% than CT), while under NT-R and NT-M grain yield was +17% higher than that under CT (Table 3). The highest plant height detected under CT [on average, 20 cm higher than that recorded under NT-V; 13 cm higher than that under NT-M; and 9 cm higher than that under NT-R (Table 4)], affected positively the straw yield, which was the highest under CT (+ 32% than NT-V; +6% than NT-M; and +4% than NT-R). That, in turn, reflected negatively on HI, which was more than 10% lower under CT, than under all NT-CCs treatments (Table 3).

As for wheat and maize, total N uptake of soybean followed a similar pattern to that of grain yield and it was not affected by different treatments (Table 3).

The Spearman rank coefficient showed a negative correlation between grain yield and rainfall pattern under NT-R, while under NT-V grain yield and precipitation were positively correlated (Table 5).

Under CT and NT-M, no significant correlation was observed, although the relationship between grain yield and rainfall tended to be positive under CT and negative under NT-M. Since the irrigation was applied homogeneously to the experimental field to compensate for the rainfall shortage and to prevent water stress, yield and irrigation were never correlated.

3.3. Dry biomass, N concentration, and N uptake of cover crops

The aboveground biomass of cover crops was affected by CC type under NT only in 2014-2015 (Table 6), when dry biomass in the CCs mixture was higher than that in hairy vetch. On the other hand, the concentration of N in the aboveground biomass was significantly different in 2012-2013 and 2014-2015: in both years, the highest value (about 39 g kg^{-1}) was detected for hairy vetch, and the lowest for rye (16.3 and 11.7 g kg^{-1}, respectively). N uptake was different among CCs in the first two years: in 2012-2013, N uptake was significantly greater with hairy vetch than with rye; in 2014-2015, it was higher with hairy vetch and mixture than with rye.

3.4. Soil organic matter, total Nitrogen, and available Phosphorus

SOM concentration in the 0-30 cm soil layer was significantly affected by tillage treatments and all NT-CCs increased SOM concentration in the 0-30 cm soil layer after the six-year experiment (Fig. 2a). SOM concentration under CT was 23% lower than that under NT-R and 19% and 17% lower than that under NT-M and NT-V, respectively (Fig. 2a). The highest average value of SOM concentration was observed under NT-R (+1.5 g kg^{-1} than NT-M; +2.0 g kg^{-1} than NT-V;

Table 3
Crop yields and N uptake of CT and NT treatments from 2011 to 2017. For each year values followed by different letters are significantly different ($p < 0.05$). P-values are also reported.

Year	Crop	Treatment	Grain Yield (Mg ha^{-1})		Straw/Stover Yield (Mg ha^{-1})		Total Biomass (Mg ha^{-1})		Harvest Index		N Uptake (kg ha^{-1})	
2011–2012	**Winter wheat**	**CT**	8.59		7.48		16.07		0.53		244	
		NT-R	9.21		7.52		16.73		0.55		252	
		NT-V	9.34		7.49		16.83		0.56		265	
		NT-M	8.92		7.92		16.84		0.53		241	
		P-value	0.0735		0.4771		0.2043		0.2484		0.2193	
2013	**Maize**	**CT**	13.09		13.75		26.85		0.49		266	
		NT-R	11.80		13.28		25.08		0.47		248	
		NT-V	11.97		14.35		26.32		0.46		271	
		NT-M	12.57		14.25		26.82		0.47		271	
		P-value	0.3572		0.2769		0.3695		0.1068		0.1856	
2014	**Maize**	**CT**	14.15		12.05		26.20		0.54		274	
		NT-R	12.87		11.11		23.99		0.54		233	
		NT-V	12.48		10.94		23.42		0.53		219	
		NT-M	14.41		13.07		27.84		0.54		302	
		P-value	0.4404		0.4370		0.4195		0.7997		0.0939	
2015	**Soybean**	**CT**	3.30	ab	3.69	a	6.99	ab	0.47	b	252	
		NT-R	3.88	a	3.56	ab	7.44	a	0.52	a	269	
		NT-V	3.21	b	2.80	b	6.02	b	0.53	a	233	
		NT-M	3.86	a	3.48	ab	7.34	ab	0.53	a	276	
		P-value	**0.0282**		**0.0150**		**0.0250**		**0.0019**		0.0589	
2015–2016	**Winter wheat**	**CT**	7.58	a	7.29		14.87		0.51		177	ab
		NT-R	6.32	b	6.94		13.25		0.48		149	c
		NT-V	7.48	a	8.38		15.85		0.47		183	a
		NT-M	6.42	b	7.41		13.82		0.46		156	bc
		P-value	**0.006**		0.6008		0.2360		0.3670		**0.0332**	
2017	**Maize**	**CT**	11.03		9.56		20.58		0.54		253	
		NT-R	11.41		9.76		21.17		0.54		270	
		NT-V	11.07		9.66		20.73		0.53		260	
		NT-M	11.02		9.58		20.60		0.54		263	
		P-value	0.6087		0.7656		0.8426		0.5516		0.5091	

Table 4
Plant height, plant density and spike density of CT and NT treatments from 2011 to 2017. For each year values followed by different letters are significantly different ($p < 0.05$). P-values are also reported. n.a. = not available.

Year	Crop	Treatment	Plant height (cm)		Plant density (n. m^{-2})	Spike density (n. m^{-2})
2011–2012	**Winter wheat**	CT	94	b	128	677
		NT-R	97	ab	118	598
		NT-V	100	a	112	626
		NT-M	98	ab	129	575
		P-value	**0.0463**		0.2148	0.2199
2013	**Maize**	CT	287		7	9
		NT-R	281		8	9
		NT-V	284		9	8
		NT-M	292		9	8
		P-value	0.3348		0.1788	0.2751
2014	**Maize**	CT	334	a	7	7
		NT-R	318	b	7	6
		NT-V	321	b	7	6
		NT-M	322	b	7	7
		P-value	**0.0326**		0.6681	0.0886
2015	**Soybean**	CT	92	a	32	n.a.
		NT-R	83	b	35	n.a.
		NT-V	72	c	35	n.a.
		NT-M	79	bc	33	n.a.
		P-value	**0.0002**		0.2351	–
2015–2016	**Winter wheat**	CT	85		230	426
		NT-R	89		217	400
		NT-V	92		225	406
		NT-M	85		201	357
		P-value	0.4015		0.0845	0.1411
2017	**Maize**	CT	228		8	8
		NT-R	220		8	8
		NT-V	221		8	8
		NT-M	222		8	8
		P-value	0.0721		0.6531	0.5974

Table 5
Spearman rank correlation coefficients between grain yield and rainfall and irrigation. P values are reported.

Treatment	Variable	Rainfall		Irrigation	
		ρ	p-value	ρ	p-value
CT	Grain yield	0.3877	0.0612	0.0304	0.8879
NT-R		**−0.5780**	**0.0031**	0.1377	0.5212
NT-V		**0.4194**	**0.0413**	0.3178	0.1213
NT-M		−0.3771	0.0693	0.2950	0.1617

and $+6.3$ g kg^{-1} than CT). In particular, SOM was considerably greater under NT-R than under CT [+ 90% in the topmost soil layer (0-5 cm)] and, within NT-CCs treatments, NT-R and NT-M tended to have the highest SOM concentration. No difference among tillage treatments was observed in the 5-15 cm soil layer, while SOM concentration in the 15-30 cm soil layer was significantly higher under NT-R (+25%) than under CT. SOM concentration in the 15-30 cm soil layer under NT-V and NT-M, instead, did not differ from NT-R or from CT.

Tillage treatments did not result in any significant difference in SOM concentration with regard to the deeper soil layers (30-45 and 45-60 cm).

STN concentration was significantly higher under all NT-CCs treatments than under CT in the 0-5 cm soil layer (80% higher under NT-V and NT-R, and 67% higher under NT-M than under CT) (Fig. 3a). No difference in STN concentration in the 5-15 and 15-30 cm soil layers was found. As for SOM, six years of NT and CCs management generally increased STN concentration in the 0-30 cm soil layer: STN was 28% higher under NT-R and NT-V and 21% higher under NT-M than under CT (Fig. 3a).

No difference in STN was observed in soil layers deeper than 30 cm (Fig. 3b), although NT-V tended to increase STN concentration also in the 30-45 and 45-60 cm layers.

Table 6
Yield, N concentration in biomass and N uptake of cover crops. For each year, values followed by different letters are significantly different ($p < 0.05$). P values are also reported.

Year	Cover Crop	Dry biomass yield (Mg ha^{-1})		N concentration in dry biomass (g kg^{-1})		N uptake (kg ha^{-1})	
2012-2013	**Rye**	3.05		16.3	c	49.8	b
	Hairy vetch	3.00		38.6	a	115.9	a
	Mix	3.14		26.3	b	82.7	ab
	P-value	0.1032		**< 0.0001**		**0.0002**	
2014–2015	**Rye**	2.85	ab	11.7	c	33.3	b
	Hairy vetch	2.09	b	38.9	a	81.2	a
	Mix	3.23	a	20.5	b	66.2	a
	P-value	**0.0499**		**< 0.0001**		**0.0028**	
2016-2017	**Rye**	2.23		28.2		62.9	
	Hairy vetch	1.88		46.1		86.6	
	Mix	1.86		37.3		69.3	
	P-value	0.4832		0.1955		0.2935	

At the end of the experiment, the soil C:N ratio was 11.1; 11.6; 10.6; and 11.3 under CT, NT-R, NT-V, and NT-M, respectively (P = 0.1015).

The available P concentration was not significantly affected by tillage in all soil layers (Fig. 4). However, all NT-CCs treatments tended to show higher available P concentrations than CT, mainly in the top soil layer (0-5 cm). In the 5-15 and 15-30 cm soil depths, NT-V tended to have more available P than the other treatments: the average value of available P under NT-V was 36% higher in the 5-15 cm layer and 38% higher in 15-30 cm layer than under CT at the same soil depth.

4. Discussion

4.1. Effects of NT and cover crops on yield, N uptake, and growth conditions of winter wheat, maize, and soybean

Consistent with our initial hypothesis, NT with CCs (rye, hairy vetch, and mixture) generally did not reduce the yield of winter wheat, maize, and soybean compared with CT without CCs (Table 3), which is the traditional management way in conventional agroecosystems. Therefore, our results corroborated previous findings on short-term field experiments reporting that crop productivity is not negatively affected by NT under temperate climates when nitrogen is not a limiting factor (Tabaglio and Gavazzi, 2006; Alvarez and Steinbach, 2009; Fiorini et al., 2020a). The findings of the present study are also in agreement with the results of Pittelkow et al. (2015), who reported in a recent meta-analysis that the possible negative gap induced by NT might disappear if crop rotation and residue retention practices were to be implemented together with NT. Rusinamhodzi et al. (2011) observed that rotating the main crops and retaining crop residue on the soil surface may significantly reduce the unfavorable effects of increased soil compaction under NT in the initial years (Vogeler et al., 2009). Introducing CCs may help to increase soil organic matter and nutrient cycling (Fageria et al., 2005; Blanco-Canqui et al., 2011; Fiorini et al., 2020b), thus enhancing crop productivity under NT (Alvarez et al., 2017). In addition, the importance of the roots of CCs as players in the "bio-drilling" process to contrast soil compaction is well known (Fiorini et al., 2018).

Under the conditions of our experiment, the grain yield of winter wheat was not negatively affected by NT-CCs in 2012 (Table 3). This was consistent with results by Perego et al. (2019), who found similar wheat grain yields between NT and CT in a comparative 3-year study on 20 farms in Northern Italy. The absence of yield reduction under NT in the first year after conversion in our experiment was probably due to a higher amount of water stored in NT soil at the grain filling stages, as previously observed by De Vita et al. (2007) and Mazzoncini et al. (2008). These authors found that NT has a positive impact on wheat grain yield when rainfall is scarce during the grain filling stage. Guzzetti et al. (2020) found similar results with cowpea cultivation under NT *vs* CT and water stress conditions in another study on the same field. The cumulative rainfall of the May-June period was, in fact, 68 mm (Fig. 1), 50% lower than the long-term (20 years) average in the same period (135 mm).

The positive effect of NT on the growth conditions of winter wheat plants in drought years (Hemmat and Eskandari, 2006) was also confirmed in our study by the higher plant heights under all NT-CCs than under CT in 2012, although this was significant only in NT-V (Table 4). It has been reported that adopting NT may immediately reduce the water loss from the soil through evaporation (Hobbs et al., 2008). Such a higher water-retaining capacity of NT soil allows to better matching plant requirements in terms of water volume and distribution timing when water inputs are scarce (Farooq et al., 2011).

Conversely, when rainfall during the grain filling stages was high

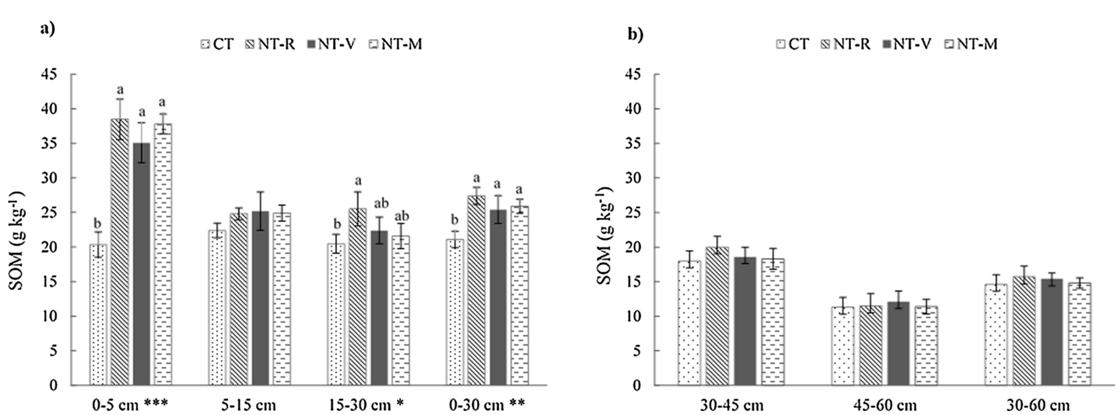

Fig. 2. Mean Soil Organic Matter (SOM) of different treatments in the 0-30 cm (a) and in the 30-60 cm (b) soil layers in 2017. Mean values ± standard deviation *, **, *** indicate significance at $P < 0.05$, 0.01, 0.001, respectively.

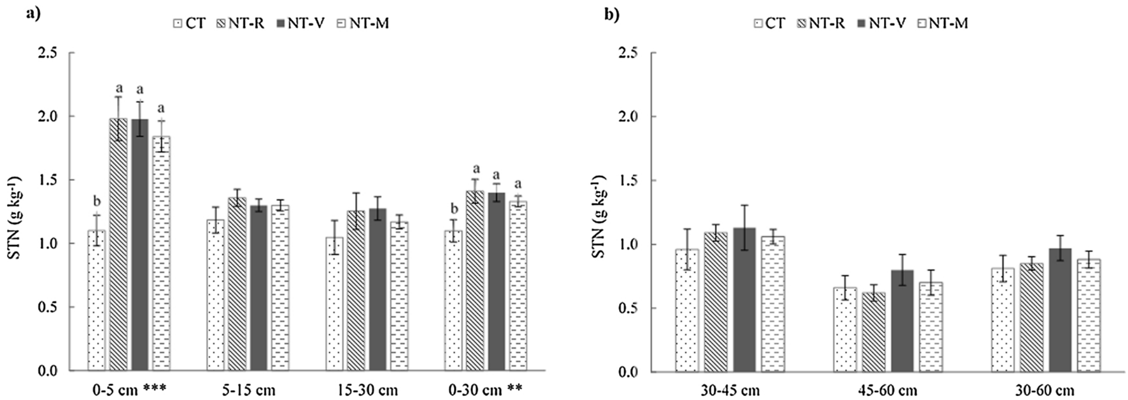

Fig. 3. Mean Soil Total Nitrogen (STN) of different treatments in the 0-30 cm (a) and in the 30-60 cm (b) soil layers in 2017. Mean values ± standard deviation. *, **, *** indicate significance at P < 0.05, 0.01, 0.001, respectively.

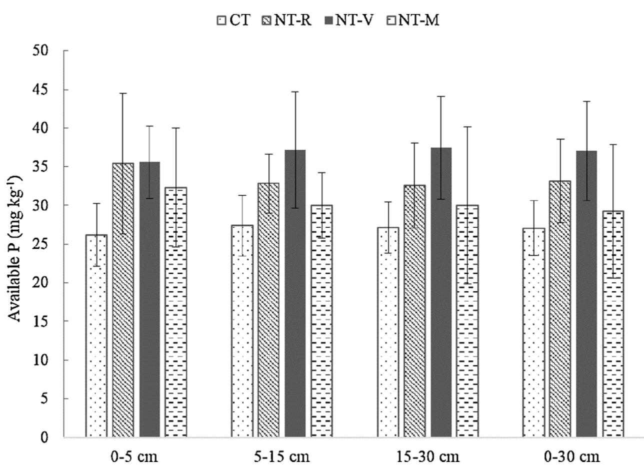

Fig. 4. Mean Soil Available Phosphorus of different treatments in the 0-30 cm soil layer in 2017. Mean values ± standard deviation. *, **, *** indicate significance at P < 0.05, 0.01, 0.001, respectively.

(119 mm; 2016), the increased water-retaining capacity of soil under NT compared with CT was of less importance, and the grain yield of winter wheat under NT (i.e. NT-R and NT-M) was about 15% lower than that under CT (Table 3). This finding is in line with Van den Putte et al. (2010), whose in a meta-regression analysis on 47 studies found a lower wheat grain yield under NT than under CT when water is not a limiting factor.

Such a yield reduction of winter wheat in our study (2016) could be ascribed to a probable lower N availability for winter wheat under NT-M and NT-R than under CT and NT-V, because rye and mixture residues were mainly non-leguminous-derived CCs residue, which are notoriously characterized by a high C:N ratio (Sainju et al., 2005). As observed by Malhi et al. (2001), when residues with a high C:N ratio are retained for several years on the soil surface, a relatively higher rate of N derived from the application of chemical fertilizers may be necessary to compensate for N immobilization losses, especially when N fertilizer is not incorporated. This did not occur under NT-V plots, where the yield of winter wheat was comparable to that under CT.

Grain yield of maize was never significantly affected by tillage, although grain production tended to be: (i) lower under all NT-CCs than under CT in 2013; (ii) lower under NT-R and NT-V than under CT and higher under NT-M than under CT in 2014; and (iii) almost the same in 2017 (Table 3). These outcomes are consistent with results obtained in a previous 3-year field experiment conducted by Tabaglio and Gavazzi (2009) in the Po Valley. These authors reported that grain yield and total biomass of maize under NT were on average 8% lower than those obtained under CT management, but not significantly different during the transition period. In addition, the gap between CT and NT gradually decreased during the experiment until, in the final year, NT-grain yield tended to outmatch that of CT. This is because the physical conditions and fertility in the topsoil usually tend to improve in the medium-long term under NT (McVay et al., 2006), thus positively affecting root growth of plants and grain yield, especially if cover cropping is adopted (Chen and Weil, 2011; Fiorini et al., 2018).

Under our experimental conditions, the plant height of maize was significantly higher (+14 cm) under CT than under NT-CCs in 2014 (Table 4). It has long been known that direct seeding into wet and cool soils is frequently related to reduced internode length (Loeppky et al., 1989). Moreover, the plant height under NT-CCs was negatively affected by the higher soil compaction in NT soil than in CT soil, revealed by the significantly higher penetration resistance in the 0-10 cm soil layer and by the considerably higher bulk density, which were detected in a previous study on the same field (Fiorini et al., 2018). Sowing at the proper depth below residue and a uniform germination are required to achieve good plant development, especially during the transition phase. Uneven germination and poor establishment of the maize plants may be affected by the incomplete closure of the no-till seed furrows, causing a lower degree of soil-seed contact: this was observed in the presence of thick mulch residue at the soil surface (Chen and Weil, 2011). Proper no-till machinery and precise regulations are needed for achieving uniform seed depth, better soil-seed contact and good drainage of excess soil water (Derpsch et al., 2014).

In our study, the grain yield of soybeans was higher under NT-R and NT-M than under CT and NT-V (Table 3). Similar results were documented in earlier studies conducted in other regions by Pedersen and Lauer (2003) and Alvarez and Steinbach (2009). These authors reported that NT maintains or even improves the grain yield of soybeans compared with CT under fine-textured soil conditions and temperate climate. In addition, Williams et al (2000) found that planting soybeans after a gramineous cover crop might increase grain yield compared with CT because of reduced weed pressure and competition. Allelopathic weed control of gramineous cover crops, especially of rye, has been previously reported (Schulz et al., 2013; Tabaglio et al., 2013).

Similarly to maize, the significantly shorter plant height of soybean could be explained by an increase in penetration resistance and bulk density in the top 20 cm of soil depth under NT-CCs in 2015 (Fiorini et al., 2018), which suggest a higher soil compaction under NT than under CT. The increase in soil compaction affects negatively soybean root growth and nodulation, leading to decreased biomass production, mainly in heavy soils (Buttery et al., 1998).

Whereas it is widely recognized that NT management can perform better than CT in terms of grain yield in dry climates and for rainfed crops (Hobbs et al., 2008; Farooq et al., 2011), results are sometimes contradictory when NT is adopted in irrigated croplands (Pittelkow et al., 2015). In our climatic conditions, rainfall is usually enough for sustaining crop growth during the first stage of the spring crops growing cycle (Fig. 1; Table A1), and irrigation is generally applied in July and August. The negative correlation observed in our experiment under NT-R between grain yields and rainfall (Table 5) could be due to the presence of thick surface mulch. This conserves soil water by decreasing evaporation and promoting infiltration during dry periods (Weil and Kremen, 2007), but may cause a reduction in soil temperature (-2 to −6 °C) and plant growth in the initial stages during rainy and cold periods (Halvorson et al., 2006), mainly in soils with high water-storage capacity. Although the amount of dry biomass was not the greatest in the present study (Table 6), rye residues disappeared more slowly than vetch residues due to the higher C:N ratio reported in a previous field study (Fiorini et al., 2020a, 2020b), thus providing abundant surface mulch during spring. A similar tendency was observed under NT-M, where mixture residues were mainly gramineous-derived, although the correlation was only close to significant. On the contrary, under NT-V, vetch residues with low C:N ratio usually disappear quickly after termination (Radicetti et al., 2016). Such fast residue decomposition has reportedly failed to exert a cooling effect on soil temperature comparable to that of rye (Teasdale and Mohler, 1993), leading to quicker soil drying. As a result, the main crops that followed benefited from rainfall in the first stages of growth, as demonstrated by the positive correlation between yields and precipitation.

Recent predictions for Italy suggest an increase in temperature of 1.7 °C in summer and a reduced and variable annual distribution of rainfall within the next 30 years (ISPRA, 2015). During the entire experiment, we observed that annual temperature was increased by 0.5 °C and rainfall was reduced by 10% compared with the 20-year average; the rainfall shortage was 82 mm between June and September, while a slight increase (+19 mm) occurred between March and May, compared with the long-term average. It follows that, due to the current context of global climate change, the choice of cover crop species should be also adjusted in irrigated croplands taking into account both the characteristics of mulch and the soil texture, which strongly affect water-storage capacity during rainy seasons (Bodner et al., 2015) and, consequently, crop growth.

4.2. Dry biomass and N uptake as influenced by cover crop type

Significant differences were observed among the three types of cover crops in terms of aboveground biomass yield in two out of three years. Mixture showed a greater yield than vetch monoculture (Table 6) in 2014-2015, as was observed in several earlier studies (Clark et al., 1994; Kuo and Jellum, 2002; Sainju et al., 2005). Such positive interactions are largely considered a result of complementarity of plant traits or of facilitation, which occurs when a species may favorably promote the growth of a neighboring species, possibly by enhancing resource acquisition or reducing stress or disturbances (Li et al., 2014).

In our study, aboveground biomass yield and N uptake by rye ranged from 2.2 to 3.1 Mg ha^{-1} and from 33 to 63 kg N ha^{-1}, respectively. The corresponding values with hairy vetch were from 1.9 to 3.0 Mg ha^{-1} and from 81 to 116 kg N ha^{-1}. Similar results were previously found by Kuo and Jellum (2002) for an early-April termination on silty-loam soil. Such a low biomass production of CCs in our study in 2016-2017 could be attributed to rainfall shortage which occurred during the growing season (216 mm from October to April, while the long-term average for the same period was 469 mm) (Table A1) and to earlier spring termination (7th of April) in 2016 due to the earlier planting of maize (Table 2). Indeed, higher values have been detected when cover crops were suppressed later in spring: Sainju et al. (2005) reported that dry biomass ranged from 2.3 to 6.1 Mg ha^{-1} for rye and from 2.4 to 5.1 Mg ha^{-1} for hairy vetch when terminated in late April, while N uptake ranged from 25 to 68 kg N ha^{-1} for rye and from76 to165 kg N ha^{-1} for hairy vetch. N concentration in the biomass differed significantly among cover crops in the first two years, when the termination was delayed, while in 2016-2017 no differences were found (Table 6). Clark et al. (1994) observed that cover crops yield significant increases (from 83 to 159%) when passing from an early spring (early April) kill to a late spring (early May) kill, while N concentration in biomass usually tends to decrease. This suggests that, in our soil-climate conditions, mulching production derived from cover crops could potentially increase even more if field management were to delay the termination date.

4.3. Effect of no till and cover crops on the status of soil fertility

Conversion from CT to NT in the present study considerably increased SOM concentration in the topsoil (0-30 cm) (Fig. 2a). In particular, this resulted from an almost doubled SOM content in the 0-5 cm soil layer under all NT-CCs treatments, compared with CT (Fig. 2a). Such an increase has to be attributed to the higher C input under NT than under CT due to residue from cover crops left on the soil surface in addition to residue from the main crops. In addition, lower biological oxidation of SOM under NT soil than under CT is well known (Chan et al., 2002; He et al., 2011). This effect, especially in the surface soil layers (0 to 5–10 cm), has long been documented. Kern and Johnson (1993), in their review encompassing seventeen studies in the USA, reported that NT increased SOC compared with CT (+ 0.7 up to +1.8 kg C m^{-2}), mostly in the topmost 8 cm. Similarly, Koch and Stockfisch (2006) reported that in Germany conservation tillage led to an accumulation of SOM in the uppermost soil layer compared with CT (0–10 cm). He et al. (2011) found that SOM in the surface soil layer (0–10 cm) was significantly greater (+16%) eleven years after the conversion from CT to NT. This is particularly the case when NT is applied in combination with residue retention and permanent soil cover practices (FAO, 2011), since increasing the input of fresh organic matter (residues from main crops and cover crops) periodically left on the soil surface generally enhances SOM accumulation (Sapkota et al., 2012; Duval et al., 2016). Conversely, tillage increases oxygen concentration in the subsoil, promotes a physical contact between residues and soil microorganisms (Coppens et al., 2006), and accelerates the turnover of soil aggregates (Six et al., 2000), resulting in significant SOM losses (Paustian et al., 1997; Balesdent et al., 2000).

Rye as a cover crop may further increase SOM concentration also in deeper soil layers (e.g., 15-30 cm) as previously observed by Sainju et al. (2006) in a 3-year experiment conducted in Georgia (USA). This was corroborated by our results (Fig. 2a), which showed the highest SOM concentration in the 15-30 cm soil layer under NT-R. Higher SOM concentration with rye as cover crop than with the other CCs or CT could be primarily due to the greater amount of C returned to the soil from the roots of the rye plant, which have been known to produce more belowground biomass than leguminous cover crops (Kuo et al., 1997; Ranells and Wagger, 1997). In addition, rye roots have a higher C:N ratio than the roots of leguminous CCs (Sainju et al., 2005); this in turn increases the amount of C stocked in deep soil layers (Kuo et al., 1997). Furthermore, the high amount of rye residues combined with a greater abundance of earthworms under NT as compared to CT, observed in a previous study on the same field (Fiorini et al., 2020a, 2020b), may have further enhanced the downward movement of SOM into deeper soil layers.

Nitrogen is a main component of SOM and similar patterns of SOM and STN concentration have been previously reported (Halvorson et al., 2002; Gál et al., 2007). In the present study, all NT treatments increased STN in the topmost soil layer (0-5 cm) compared with CT, and generally tended to increase STN content also in the 5–15 cm soil layer (Fig. 3a). Similar results were found by Halvorson et al. (2002) in a 12-year study on silty-loam soil. Such increase in the shallow soil layer led to an overall higher STN in the 0-30 cm layer under NT than under CT; under NT-R and NT-V STN, in particular, was nearly 28% higher than under CT, underlining the importance of cover crop cultivation for increasing STN and reducing N fertilizer requirements (Tonitto et al., 2006). This is particularly the case when a leguminous CC is cultivated: Mazzoncini et al. (2011), in a research conducted in Central Italy, showed that 10-year leguminous cover cropping increased STN concentration in the 0-30 cm layer by 11%.

However, our findings suggest that not only hairy vetch but also rye may increase STN under NT (Fig. 3a). Such an increase is commonly attributed to the rise of net N immobilization, due to the accumulation of high C:N residues at the soil surface (Kuo and Sainju, 1998). In addition, the overall higher N content under NT than under CT in our study was also due to a lower nitrogen mineralization rate (Malhi et al., 2001). In tilled soils, the N mineralization rate rises compared with untilled ones, and this is the consequence of: (i) the rise in soil temperature when crop residues are not present on the soil surface (Fabrizzi et al., 2005); (ii) the increased soil aggregates break-down due to tillage which exposes physically-protected N pools to the mineralization process (Six et al., 2002); and (iii) the increase in the residue decomposition rate and subsequent nitrogen release (Lupwayi et al., 2006). Conversely, the lower soil disturbance under NT may reduce N mineralization and STN loss (Malhi et al., 2001).

The high C and N inputs due to residue contribution under NT often lead to a low decomposition rate of the organic matter in the surface soil (Six et al., 2002). This usually results in a higher soil C:N ratio in the top soil layer under NT than under CT (Lou et al., 2012). However, in our experiment, at the end of the study the soil C:N ratio was similar between CT and NT-CCs treatments ($P = 0.1015$) as both soil C and N increased under NT-CCs and decreased under CT.

The concentration of SOM and its mineralization rate can also affect P concentration in soil. SOM plays a major role in promoting soil processes involved in P transformation, through its contribution as energy source to microbial activity. Microorganisms are involved in P transformation through the decomposition of organic P compounds, with the consequent freeing of available P, and the immobilization of available P into cellular material (Paris et al., 2004). Our results showed that available P concentration tended to increase in the 0-30 cm soil layer under NT compared with CT (Fig. 4). Many studies found that the presence of residues at the soil surface generates higher available P concentration under NT than under CT near the soil surface (Martin-Rueda et al., 2007; Obour et al., 2017). However, the findings of some trials showed a higher P concentration under NT than under CT also below 15-cm soil depth (Rhoton, 2000; Motta et al., 2002). Motta et al. (2002) found that long-term accumulation of crop residues under temperate conditions, combined with the presence of earthworms and root channels, which are preferential pathways for the movement of water and nutrients, could promote the downward movement of organic P under NT.

Hallama et al. (2019) observed that cover crops revealed a greater ability to access slightly available soil P than cash crops, owing to: i) a greater soil volume exploration due to an adaptive root architecture and root morphology; ii) the mobilization of moderately-soluble inorganic and organic forms of P; and iii) the mineralization of organic P. All these mechanisms could be improved through interaction with soil microbes. In the present study, the tendency of available P concentration to increase especially under NT-V in the 5-30 cm soil layer could be explained by the ability of some leguminous crops to convert fairly unavailable P forms (native or derived from residual fertilizers) into more extractable chemical forms (Cavigelli and Thien, 2003). In fact, our results showed that under NT-V the available P concentration was 36% higher in the 5–15 cm and 38% higher in 15-30 cm soil layer than under CT at the same depth.

Moreover, according to Franchini et al. (2004), cover crops play a role as P transporters into the roots: these authors observed that vetch, in particular, is the cover crop with the greatest transport efficiency of P into roots from superficial to lower soil layers.

The role of cover crops for promoting P cycling, then, assumes a primary importance if we consider the growing problem of P scarcity: mineable reserves of P are indeed non-renewable and concentrated in regions with territorial conflicts (Cordell and White 2014).

5. Conclusions

Results from this 6-year field study evaluating the effects of soil tillage and cover crops on crop yield and on the status of soil fertility suggest that no-till (NT) coupled with winter cover crops (CCs) does not reduce crop yield even during the transition period, in a temperate climate and in silty-clay soil, compared with conventional tillage (CT). The composition of CC mulch may greatly affect the response of crop yields to the rainfall pattern: under NT-R, a negative correlation was observed between grain yield and rainfall, while under NT-V this correlation was positive.

No-till and continuous inputs of fresh organic matter from (cover) crop residues to the surface soil led to a consistent increase in SOM and STN levels in the 30-cm soil depth layer, mainly due to the high SOM increase in the uppermost soil layer (0-5 cm). The cultivation of rye as cover crop led to a significant SOM enhancement also in the 15-30 cm layer. Conversely, the available P concentration was not affected by the different soil and cover crop management, in spite of a tendency to increase under NT-V. However, below 30-cm soil depth, different tillage treatments did not affect SOM and STN.

Consistent with our initial hypothesis, the results of this study highlight that combining NT and CCs could be suggested for intensive croplands with fine-textured soils (such as those of the Po Valley) in order to prevent yield reduction and increase the overall status of soil fertility.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Roberta Boselli: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Andrea Fiorini:** Conceptualization, Methodology, Writing - original draft. **Stefano Santelli:** Investigation. **Federico Ardenti:** Investigation. **Federico Capra:** Investigation. **Stefania Codruta Maris:** Investigation, Formal analysis. **Vincenzo Tabaglio:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Acknowledgments

This work was supported by the Foundation Romeo and Enrica Invernizzi (Milan, Italy). We would like to thank colleagues, technicians and students from the Agronomy Group of the Department of Sustainable Crop Production (Università Cattolica del Sacro Cuore of Piacenza) for their assistance throughout the duration of the experiment, and Rosanna M. Giammanco for language editing.

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.fcr.2020.107871.

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