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Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system

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ABSTRACT

Reduction of soil tillage is of paramount importance for agricultural soil preservation. However, it is often accompanied by yield reduction and weed management problems. In this perspective, cover crops could play an important role to alleviate weed infestation and sustain yield. In this study, the results from a three-year experiment of cover crop cultivation in different soil tillage treatments is presented, together with results from DayCent simulations on the long term evolution of soil organic carbon and total nitrogen. Eight cover crop treatments were set up as subtreatments in a long term experiment in Switzerland. Cover crops were cultivated for a short two-month period between two winter wheats. Substantial differences in cover crop growth were observed depending on cover crop species. In all tillage treatments, high cover crop biomass production allowed to supress weed biomass compared to the no cover crop control. Wheat grain yield was higher in the minimum tillage than in the plough treatment. In the no till treatment, wheat yield was notably low, except in the field pea treatments, where wheat yield reached values similar to that observed in the plough and minimum tillage treatments. In addition, these differences in biomass production translated into important differences in nutrient inputs, and even in soil nutrient concentration in some cases. Long term simulations showed that cover crop cultivation could increase drastically soil organic carbon and total nitrogen, especially in reduced tillage treatments. Altogether, these results demonstrated that the presence of a well-developed cover crop, even for only two months, allows to sustain wheat yield in a no till treatment. It impacts also soil fertility and nutrient cycling. This study shows that an accurate use and management of cover crops, in interaction with tillage reduction, could maintain yield and improve soil fertility in the long term.

1. Introduction

In order to limit the environmental impact of agriculture, alternatives to traditional systems have been proposed. Conservation agriculture is one of these alternatives, which is more and more adopted worldwide (Holland, 2004). It is based on three fundamental principles: 1. diversification of crop rotation, 2. reduction of soil tillage and 3. permanent soil cover (FAO, 2017). Compared to classical plough tillage, reduced tillage has several advantages, such as reduction of fuel costs, decreased disturbance for soil organisms, preservation of soil fertility, higher soil macroporosity, better water retention (Holland, 2004; Lienhard et al., 2013; Mazzoncini et al., 2011; Murugan et al., 2014; Palm et al., 2014; Sapkota et al., 2012; Soane et al., 2012). In contrast, detrimental effects, such as increased soil density, reduction of mineralisation or slowing of soil warming, could be observed in reduced tillage systems, especially with direct seeding (Soane et al., 2012). Reduced tillage also influences soil cover through a higher retention of crop residues at soil surface, compared to ploughing which incorporates residues in the soil. Another way to increase soil cover throughout the rotation is to integrate cover crops between two main cash crops. In temperate European regions, the long period running between summer harvest and the seeding of spring crops is obviously favourable for the implementation of cover crops. However, shorter periods such as the 2–3 months between summer harvest and the seeding of winter crops can also be suitable for the seeding of cover crops. Cover crops are expected to offer several services within the agroecosystems. In particular, they protect the soil against erosion, help to control weeds, and bring additional organic matter to the soil (Justes et al., 2012; Sainju et al., 2002; Thorup-Kristensen et al., 2003). They also accumulate large amounts of nutrients, and thus prevent their loss through lixiviation, and can improve the availability of nutrients for the next crop.

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Table 1
Description of the eight cover crop subtreatments. The 'Standard targeted plant density' is the expected plant stand when cultivated as a monoculture, while 'Targeted plant density' is the density used in this experiment. '% density' is the relative density used in this experiment, compared to the standard one.

N°	Common name	Species	Botanical family	Cultivar	Standard targeted plant density (pl/m^2)	Targeted plant density (pl/m^2)	% density
1	Brown mustard	*Brassica juncea*	Brassicaceae	Vitasso	500	500	100
2	Daikon radish	*Raphanus sativus longipinnatus*	Brassicaceae	Structurator	80	80	100
3	Field pea	*Pisum sativum*	Fabaceae	Arkta	150	150	100
4	Black oat	*Avena strigosa*	Poaceae	Pratex	400	400	100
5	Niger	*Guizotia abyssinica*	Asteraceae	Azofix	300	300	100
6	Phacelia	*Phacelia tanacetifolia*	Hydrophyllaceae	Balo	500	500	100
7	11 species mixture						
		Sinapis alba	Brassicaceae	Albatros	300	19	6.25
		Raphanus sativus longipinnatus	Brassicaceae	Structurator	80	5	6.25
		Vicia faba	Fabaceae	Fuego	80	16	20
		Lens culinaris	Fabaceae	Lenti-fix	200	40	20
		Pisum sativum	Fabaceae	Arkta	150	15	10
		Setaria italica	Poaceae	Extenso	400	25	6.25
		Sorghum sudanense	Poaceae	Hay-king	200	13	6.25
		Helianthus annuus	Asteraceae	Iregi	80	5	6.25
		Phacelia tanacetifolia	Hydrophyllaceae	Balo	500	31	6.25
		Fagopyrum esculentum	Polygonaceae	Lilea	200	13	6.25
		Linum usitatissimum	Linaceae	Princess	500	31	6.25
8	control	non seeded					

However, the beneficial effect of cover crops in the whole system, and on the following crop, depends strongly on their management (e.g. choice of species, seeding and destruction time), and is not always easily demonstrated (Tonitto et al., 2006). An interaction with soil tillage could be expected for several reasons. Some cover crop species are particularly sensitive to seedbed preparation (e.g. phacelia) and are not expected to be well suited for direct seeding. Intensity of tillage before cover crop seeding could also influence mineralisation rate, or water availability, which could in turn affect cover crop emergence and growth. Therefore it is crucial to study the introduction of cover crops in agroecosystems in interaction with different tillage practices used on a long term.

The objectives were 1. to assess cover crop performance in interaction with soil tillage, and their effect on the yield of the following wheat, 2. to determine whether and which combination of treatments allows to exceed the yield of the classical system plough without cover crops, 3. to study the short term effects of three years of cover crops in terms of soil fertility and to evaluate the long term potential for soil fertility improvement through cover crop cultivation using DayCent simulations.

In the present study, eight different cover crop treatments were integrated in a long term experiment of soil tillage established in 1969. Three tillage treatments were used, going from classical plough tillage to minimum tillage and no till. As these tillage treatments had accumulated 44 years of differences when this specific experiment took place, they should be seen as different systems rather than classical factorial treatments. The standard crop rotation was interrupted to investigate the performance of cover crops in a short period of time, between two winter wheats. This sequence was repeated three times in order to also address cumulated effects.

2. Materials and methods

2.1. Long term experiment

The long term experiment was established in 1969 in Agroscope Changins (46°24′ N, 06°14′ E, 430 m above sea level), Switzerland. In this site, the mean annual temperature is 10.2 °C and the average total annual precipitation is 999 mm (30-year averages, 1981–2010). The experiment is set up on two different types of soil, a clay (48% clay-37% silt) and a loam (25% clay-44% silt) soil.

The experiment follows a randomized complete block design with three main treatments of soil tillage; conventional deep inversion tillage on one side, and two reduced tillage treatments on the other side (Büchi et al., 2017). Until 2007, the following treatments were applied: T1. deep inversion tillage (plough), T2. deep non inversion tillage, T3. minimum tillage. In 2007, the deep non inversion tillage treatment (T2) was converted into a no till treatment (last tillage: autumn 2006). Each treatment is replicated three times on the clay soil and four times on the loam soil.

The crop rotation is winter wheat, winter rapeseed, winter wheat, grain maize. In 2013, the standard rotation was interrupted to allow the setup of the present experiment, which took place between August 2013 and July 2016.

At that time, 44 years of differentiated tillage practices have modified soil properties in each treatment (Büchi et al., 2017). Though organic carbon (C) stocks were not significantly different between tillage treatments in 2013, the plough and deep non inversion tillage treatments showed a marked decrease of C concentration since the beginning of the experiment, while the minimum tillage treatment allowed to maintain C concentration. In addition, an important C and nutrient stratification with depth was observed in this treatment.

2.2. Experimental setup

In August 2013, after the harvest of a winter wheat (straw exported), each main plot was divided into eight subplots to integrate cover crops. The size of each subplot was 3 m × 8.75 m, which represented a surface of 26.25 m^2. Eight different treatments were considered: 1. brown mustard (*Brassica juncea*), 2. daikon radish (*Raphanus sativus longipinnatus*), 3. field pea (*Pisum sativum*), 4. black oat (*Avena strigosa*), 5. niger (*Guizotia abyssinica*), 6. phacelia (*Phacelia tanacetifolia*), 7. 11 species mixture (with 50% legumes), 8. control with no cover crop (Table 1). All species composing the 11-species mixture were studied in another experiment set up at the same site (Wendling et al., 2016). All the species used here are frost sensitive and would thus, in this region, typically die at the end of autumn (November–December).

The general management sequence was the following: cover crops were direct seeded, in all soil tillage treatments, at the beginning of August; their biomass was evaluated, together with weed biomass, at the beginning of October; tillage was then applied according to treatments, winter wheat was seeded at the end of October – beginning of November and then harvested between mid-July – beginning of August (Fig. 1). This sequence was repeated three times, in 2013–2014,

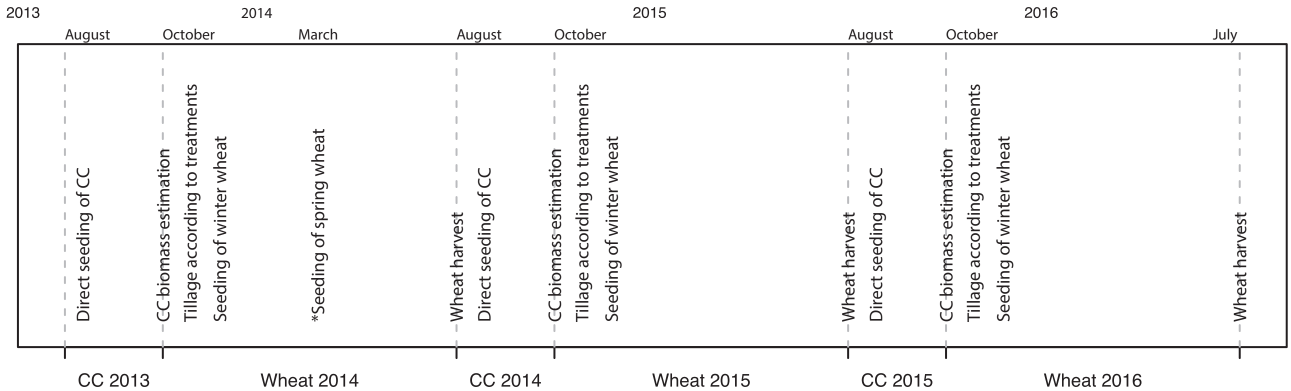

Fig. 1. Management and intervention sequence of the three years of experiment. 'CC' stands for 'cover crop'.

2014–2015 and 2015–2016.

Cover crops were seeded with an experimental direct seeder (Alphatec – Great Plains modified for small plots and different seed sizes), at 3–4 cm depth. Seeding density was adapted from recommended commercial rates to ensure a targeted plant stand and a good performance of the cover (Wendling et al., 2016, Table 1). No fertilisation was applied during cover crop cultivation. In 2014, the cover crops were irrigated twice at the beginning of September (~45 l/m^2 water in total), to insure good crop development. The termination of cover crops differed from year to year, according to their biomass production. In 2013, they were destroyed with a knife roller, whereas they were shredded with a chopper in 2014, in all treatments. In 2015, cover crops in the no till treatment were left standing, while they were shredded with a chopper in all the plough and minimum tillage treatments.

Tillage was then applied in each plot according to the respective treatments. A mouldboard plough followed by a rotary harrow was used in the deep inversion tillage (plough) treatment, while a rotary harrow alone was used in the minimum tillage treatment.

Winter wheat (*Triticum aestivum* cv. Arina) was seeded after soil tillage with the experimental seeder, at 2–4 cm depth, and at density of 500 grains/m^2 in 2013, 450 grains/m^2 in 2014 and 460 grains/m^2 in 2015. In the first year, exceptionally bad weather and soil conditions shortly after seeding prevented wheat emergence, and so spring wheat (*Triticum aestivum* cv. Fiorina, 470 grains/m^2) was seeded in replacement in March.

Nitrogen fertilisation was applied each year in two or three way splits (respectively 120 N, 130 N and 140 N in total). Herbicides were always applied to the whole experiment in order to avoid any heterogeneity of treatment. They were applied depending on weed pressure during initial wheat growth. Glyphosate was applied in 2014 and 2015 after wheat harvest, before cover crop seeding, because of a very high weed pressure. Fungicide and molluscicide were also used according to integrated crop protection principles (Häni et al., 1990). No insecticide or growth regulator were applied in this experiment. Wheat was machine harvested at maturity, independently for each subplots. Straw was exported to guarantee a better settlement and growth of the following cover crops.

Meteorological conditions differed a bit during the three years of experiment, particularly for precipitation. For the whole cultivation year, from 1st of August to 31th of July, mean temperature was 11.5 °C the first year (2013–2014), 12.1 °C for the second year (2014–2015) and 11.4 °C the third year (2015–2016). For the same time period, total precipitation was respectively 1211 mm, 918 mm and 1300 mm, 918 mm and 1300 mm. For the period from cover crop seeding to biomass sampling, precipitation was particularly low in 2014 (103 mm), and also in 2013 (200 mm), compared to 2015 (253 mm) (Supplementary Fig. S1). Growing degree days (Tbase = 0 °C) were the lowest in 2014 (1024 GDD), while 2013 (1128 GDD) and 2015 (1153 GDD) showed close values.

2.3. Data collection

At the beginning of October, after about 60 days of growth, cover crop biomass was evaluated by manual sampling. In each subplot, aboveground biomass was collected at ground level, in two 0.5 m × 0.5 m quadrats. Biomass samples were dried at 55 °C during 72 h, and then weighed to obtain dry matter biomass. It was then shredded and analysed to determine carbon (C), nitrogen (N), phosphorus (P) and potassium (K) concentration. N and C were assessed after combustion (Dumas, 1831) and P, K were measured by ICP-AES after incineration and solubilisation in hydrofluoric acid. C/N ratio was computed by dividing C content by N content. At the same time, canopy cover of all cover crops was assessed visually by trained observers. An estimation of specific composition of all mixture subplots was done shortly before biomass sampling, as the share of soil cover represented by each of the eleven species composing the mixture.

Weeds were collected at the same time as cover crop biomass evaluation, in the same quadrats, and their dry biomass was measured, independently for each sample. Weeds from the no cover crop control subplots were also analysed for nutrient concentration.

For wheat, grain was harvested by a combine harvester on a width of 2.40 m, on the whole subplot length, leaving a 30 cm width buffer on each side of the harvested area. Grain humidity was measured shortly after harvest, and yield adjusted at 0% humidity. Nitrogen concentration in grains was determined by near infrared spectrometry using a NIRS6500 (FOSS NIRSystems, Inc., Laurel, Md, USA).

Few days before the machine harvesting of the whole experiment, manual samples of wheat aboveground biomass were taken in the subplots 'field pea' (except in 2014) and 'no cover crop control'. Biomass was cut at 15 cm from the ground level, for four rows on 1 m length, and then dried at 55 °C during 72 h. Grain was then separated from the straw with a static hand harvester, and then weighed. Straw dry weight was also determined. Grain and straw was then shredded and analysed to determine nutrient concentration.

In summer 2016 (end of the experiment), soil samples were taken, for the layers 0–20 and 20–50 cm, from the 'no cover crop control' and 'field pea' subplots. Eight to ten cores were taken from each subplot to insure a good representativeness of soil characteristics. Soil samples were oven-dried at 55 °C during 72 h and then analysed for concentration in soil organic C, total N, and available P and K. P was extracted with NaHCO3 following Olsen et al. (1954), and K with ammonium acetate according to the Swiss standard methods (Agroscope, 1996).

2.4. Data analysis

The resulting experimental design corresponded to a split-plot design with seven replicates (both soils together), three tillage treatments and eight cover crop subtreatments. To focus on the effect and interactions of tillage and cover crops, results from the two soils were analysed together as a whole.

The effect of experimental year, tillage and cover crop treatments on cover crop biomass, weed biomass and wheat yield was tested using analyses of variance with replicates as random factor. Effects of cover crop treatments were also tested independently within each tillage treatment and year. Tukey 'honestly significant difference' post hoc test was performed to assess pairwise differences between cover crop subtreatments (R package 'agricolae', de Mendiburu, 2014)

Correlations between cover crop biomass, soil cover and weed biomass were performed with Kendall's rank correlation. In addition, Pearson's correlations between wheat yield on one hand, and cover crop biomass, soil cover, nitrogen uptake, C/N ratio, weed biomass on the other hand, were performed independently for each year and tillage treatments.

Total aboveground net production of each subplot was assessed by summing the biomass produced by the cover crops, by the weeds and by the wheat (grain, straw, stubble). Stubble biomass was estimated from straw data taking into account harvest height and wheat height. We estimated C inputs from the three year experiment as aboveground net production multiplied by the respective C concentration of each of its component. N inputs in the no cover crop control subplots were equal to the cumulated amounts of N fertilisation. For field pea subplots, an estimation of the amount of N biologically fixed was added to the fertilisation inputs. This was computed by multiplying pea N uptake (biomass × N concentration) by 70%, which is the mean 'N derived from the atmosphere' value of field pea in this location (Büchi et al., 2015). Nutrient exportation (C, N, P, K) was computed by multiplying grain and straw/stubble biomass by the nutrient concentration.

All analyses were performed using R 3.3.3 (R Core Team, 2017).

2.5. DayCent model

DayCent (Del Grosso et al., 2001) is a fully resolved terrestrial ecosystem model of intermediate complexity that simulates C and N biogeochemical processes in various soil-plant systems on a daily time step. It includes sub-models for plant productivity, decomposition of dead plant material and soil organic matter, soil water and temperature dynamics, N gas fluxes and CH_4 oxidation. Net primary productivity is a function of genetic potential, plant phenology, nutrient availability, soil water, temperature, shading and solar radiation. Soil organic matter, represented by plant litter and three conceptual pools (active, slow, and passive), is simulated for the upper 20 cm. Tillage options allow for the transfer of defined fractions of shoots, roots, standing dead and surface litter into standing dead, surface and soil litter pools. In addition, each tillage option has a pre-defined set of multipliers representing effects of soil tillage disturbance on soil organic matter decomposition rates for the structural, active, slow and passive pools for 30 days after the tillage event. Thus, the model allows to simulate a variety of conventional and alternative tillage methods. However, as any other biogeochemical model, DayCent does not take into account changes in soil physical properties and architecture of the soil matrix over time, nor disease, pest and weed incidence.

2.6. Modelling approach

To complement the field experiment, and assess the long term effect of cover crop cultivation in combination with tillage practices on soil organic C and total N, we used the DayCent model (Linux version 2012) to extrapolate the effects of the experimental treatments in time. This model has been already successfully used to simulate yields and soil C and N dynamics in four long term field experiments in Switzerland, including the one in which the current study took place (Necpalova et al., under review). In the later study, the model was thoroughly calibrated to represent crop yields and soil organic C dynamics under four tillage treatments in this long term experiment during the period 1969–2012. In the present study, a follow up model calibration to represent the field pea growth under four tillage treatments, using cover crop biomass and C and N content data collected over three growth cycles (2013–2016) was accomplished. The existing default crop parametrisation for field pea was modified to match the aboveground biomass (radiation use efficiency and genetic potential), temperature responses (optimum and maximum temperature for crop growth), C/N ratios of the crop aboveground biomass and biological fixation potential correctly. The calibration approach has been described in Necpalova et al. (under review). Model performance was evaluated using numerous statistical criteria (Wallach et al., 2014): root mean square error (RMSE), relative RMSE (rRMSE), coefficient of determination (R^2). Due to lack of independent data, no independent model evaluation could be carried out.

The long term simulations to evaluate the effects on soil C and N consisted of a) a spin up followed by a land use history period (0–1968), b) a period consistent with the management of the long term experiment (1969–2016), and c) a scenario analysis over 50 years (2017–2067). The spin up simulation is a standard approach of initializing the distribution of soil C conceptual pools and bringing them to the equilibrium with C inputs through the long term simulation of the native ecosystem, i.e. temperate deciduous forest in Switzerland.

In the first scenario '0cc', no cover crop was cultivated between main crops. In the second scenario '1cc', a cover crop was present 1x during each rotation, between wheat and maize. In the third scenario '2cc', a cover crop was present 2x during each rotation (between wheat and maize, and between wheat and rapeseed). In the fourth scenario '3cc', a cover crop was cultivated between main crops whenever possible (3x during the rotation), i.e. between wheat and maize, wheat and rapeseed and rapeseed and wheat. Based on the outcomes of the field experiment, in all scenarios, field pea was used as cover crop to explore the maximum potential of cover crop cultivation to alleviate the negative effects of reduced tillage and increase the fertility. The last scenario 'nostraw' was run as a control, with no cover crop and wheat residue exported (wheat residues are left on the field in the other scenarios). These five scenarios were simulated for each tillage treatment on both soils. In total, 30 independent scenarios were considered in the analysis. The simulations were driven by daily historical weather data recorded over the experimental period 1969–2016. The soil profiles were characterised using initial physicochemical properties (soil texture, bulk density, soil C and pH) from 1969. Soil hydraulic properties (field capacity, wilting point and saturated hydraulic conductivity) were calculated based on soil texture, bulk density and SOC concentration using pedo-transfer functions (Wosten et al., 1999). Field pea was directly seeded the day after the harvest of the previous main crop. In the plough treatment, the cover crop was killed and incorporated in the soil during ploughing. In the minimum tillage and no till treatments, the cover crop was killed using DayCent herbicide option on the same day as when ploughing occurred. Therefore the length of main crop and cover-crop cycles remained equal between the treatments. For all scenarios, the standard crop rotation of the long term experiment (wheat – rapeseed – wheat – maize) was adopted, beginning with a grain maize in 2017. This rotation corresponds to actual practice in Switzerland and made thus the modelling approach consistent. Cropping management (seeding and harvest dates, fertilisation, management of crop residues) was consistent with the standard dates and management in the long term experiment. The model was used to simulate the crop yield and cover crop biomass, soil organic C and total N in the 0–20 cm soil layer and annual C inputs in response to the tillage and cover crop management for the period 2017–2067.

Table 2
Analyses of variance for the cover crop biomass, weed biomass and wheat yield, independently for each year. 'CC' stands for 'cover crop' and 'df' for 'degree of freedom'. Significant *p*-values ($p < 0.05$) are in bold.

		CC biomass		weed biomass		wheat yield	
			df	*p*-values	df	*p*-values	df
2013–2014	tillage	2	0.05	2	0.075	2	**< 0.001**
	cover crop	6	**< 0.001**	7	**< 0.001**	7	**< 0.001**
	cc x tillage	12	0.9	14	0.433	14	**< 0.001**
2014–2015*	tillage	2	**< 0.001**	2	0.206	2	**< 0.001**
	cover crop	6	**< 0.001**	7	**< 0.001**	7	**< 0.001**
	cc x tillage	12	**0.012**	14	0.199	14	0.239
2015–2016	tillage	2	**< 0.001**	2	**< 0.001**	2	**0.001**
	cover crop	6	**< 0.001**	7	**< 0.001**	7	**< 0.001**
	cc x tillage	12	0.252	14	**0.005**	14	**< 0.001**

*in 2015, weed data not available for 1 over 7 replicates.

3. Results

3.1. Cover crops

Overall, the mean biomass production of cover crops was equal to 1.6 t/ha, but it varied significantly between years ($p < 0.001$). 2015 was the most productive year, with a mean of 2.9 t/ha, whereas 2013 and 2014 showed low cover crop biomass production with 1.1 t/ha and 0.8 t/ha, respectively. These differences could be partly linked to meteorological conditions, as precipitation was particularly low in 2014, during the period from cover crop seeding to biomass sampling, compared to 2015, with an intermediate value in 2013 (Supplementary Fig. S1).

When analysed independently for each year, cover crop subtreatments appeared always significant ($p < 0.001$), whereas tillage treatment was significant in 2014 and 2015 but not in 2013 (Table 2). As a whole, cover crop biomass was slightly lower in no till treatment (1.4 t/ha) compared to minimum tillage (1.7 t/ha) and plough (1.8 t/ha). The highest differences were observed between cover crop species, with mean biomass going from 2.9 t/ha for the mixture (#7) down to 0.9 t/ha for phacelia (#6). Mixture (#7) and field pea (#3, 2.5 t/ha) were clearly the two most productive cover crops, regardless of tillage treatments and years (Fig. 2), except in 2015, where field pea was only at the 5th rank (among 7 species, 1st rank for the mixture). This was, however, due to an increase in biomass for the other species and not due to a decrease in field pea biomass, which maintained almost the same biomass throughout the years and treatments.

Soil cover provided by cover crops was highly correlated with cover crop biomass (Kendall's rank correlation $\tau = 0.72$, $p < 0.001$), though field pea (93%) generally offered more soil cover than the mixture (82%), which had higher biomass.

Cover crop species showed also differences in nutrient concentration. N concentration varied from 14 mg/g (#2 daikon radish) to 42 mg/g (#3 field pea), P concentration from 3.1 mg/g (#1 mustard) to 7.3 mg/g (#5 niger), and K concentration from 22.5 mg/g (#1 mustard) to 50 mg/g (#5 niger). Carbon nitrogen ratio C/N also varied between species, going from 11 for field pea (#3) to 29 for mustard (#1) and daikon radish (#2), and between years, with globally higher values in 2015 when biomass production was higher.

The specific composition of the mixture changed from year to year. While it was clearly dominated by legumes in 2013 and 2014 (about 90% of total soil cover, assessed visually), its composition was more balanced in 2015 with about 50% legumes, 35% mustard and 15% sunflower. The mean C/N ratio of the mixture biomass changed accordingly, with C/N = 13 in 2013, C/N = 12 in 2014, and C/N = 20 in 2015 (field pea: C/N = 11 in 2013, C/N = 10 in 2014, C/N = 12 in 2015).

3.2. Weeds

Overall, mean weed biomass before wheat seeding was equal to 0.59 t/ha, and did not differed between years. It varied however significantly between tillage treatments and cover crop species (Table 2). Highest weed biomass was observed in no till plots (0.72 t/ha),

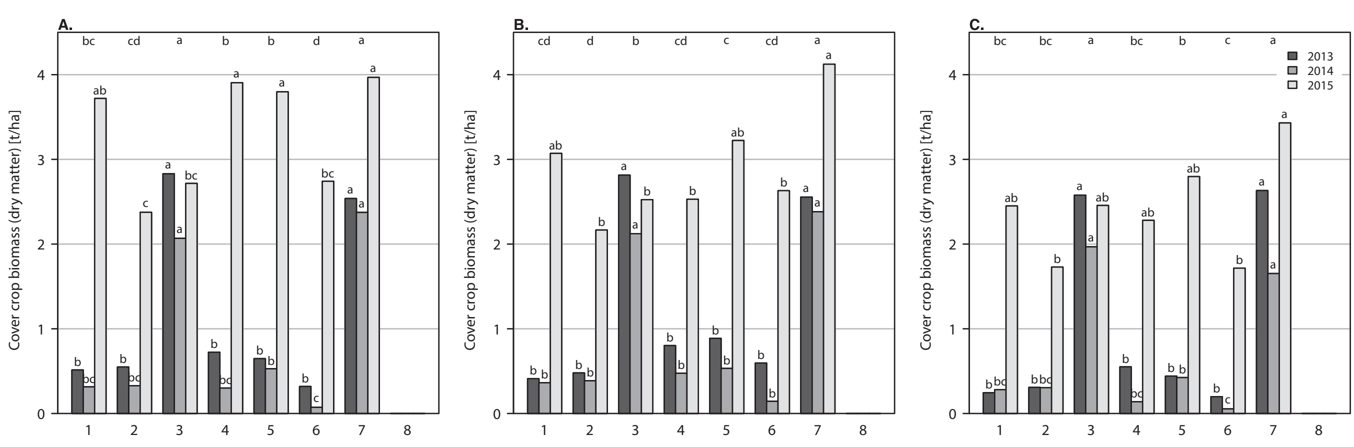

Fig. 2. Cover crop biomass [t/ha] in function of the cover crop treatments, for A. plough, B. minimum tillage and C. no till treatments. Cover crop treatments are 1. brown mustard, 2. daikon radish, 3. field pea, 4. black oat, 5. niger, 6. phacelia, 7. cover crop mixture, 8. no cover crop control. The bar colour represents the year of experiment, dark grey for 2013, grey for 2014 and light grey for 2015. Different letters (above each bar) show significant differences between cover crop treatments (tested independently for each tillage treatment and year). The letters at the top of each panel correspond to differences in mean cover crop biomass, computed over the three years.

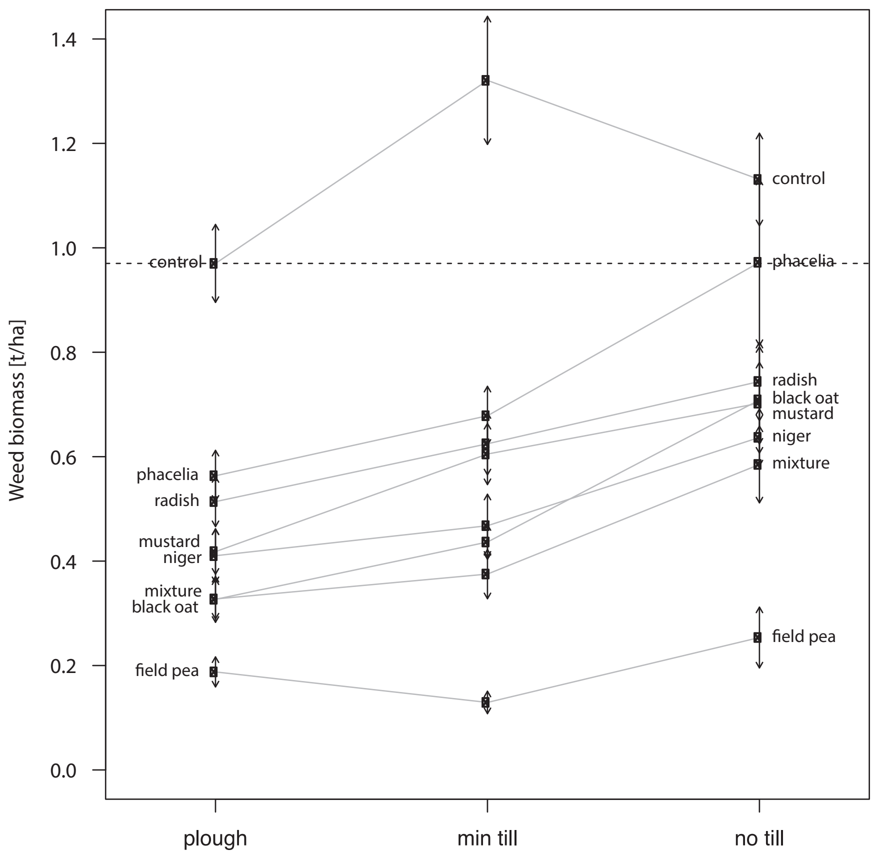

Fig. 3. Weed biomass [t/ha] in function of the tillage and cover crop treatments. Each dot corresponds to the mean biomass computed over the three years and replicates. The arrows represents +/− 1 * standard error. The horizontal dashed line shows the weed biomass observed in the plough – no cover crop reference treatment.

followed by minimum tillage (0.58 t/ha) and plough (0.46 t/ha). Mean weed biomass in the no cover crop control plots was 1.14 t/ha. Among cover crops, field pea plots were those with the lowest weed biomass (#3: 0.19 t/ha) whereas the highest weed biomass was observed with phacelia (#6: 0.74 t/ha). Looking at the performance of the different cover crop treatments in the tillage treatments, most of the cover crops allowed to decrease weed biomass below the level of the reference treatment, i.e. plough – no cover crop, even with minimum and no tillage (Fig. 3). Weed biomass in the different cover crop treatments was generally similar in all tillage treatments, except for phacelia which was particularly inefficient against weed in no till.

Weed biomass was correlated with cover crop biomass (Kendall's rank correlation tau = −0.39, $p < 0.001$). However, cover crop soil cover was a better predictor of weed biomass than cover crop biomass (Kendall's rank correlation tau = −0.43, $p < 0.001$). This was also illustrated by the fact that lower weed biomass was observed in field pea plots (high soil cover) than in mixture plots (high biomass).

After the first year of experiment, no till plots were notably invaded by rattail fescue (*Vulpia myuros*). This species produced dense carpets of plants, though having a low biomass. Weed infestation in no till plots was thus likely underestimated when assessed using weed biomass values.

3.3. Wheat

Overall, mean wheat grain yield was equal to 2.7 t/ha, which was really low compared to mean yield in the long term experiment (4.3 t/ha). Differences between years were not significant. However, tillage treatments had a strong influence on crop yield, with the highest values reached with minimum tillage (3.4 t/ha), followed by plough (3.0 t/ha) and no till (1.8 t/ha) (Fig. 4). The identity of the preceding cover crop had also a marked influence on crop yield, with more than 3 t/ha for field pea (#3: 3.6 t/ha) and the mixture (#7: 3.2 t/ha), and the lowest value observed for the no cover crop control (#8: 2.3 t/ha).

However, strong interactions between years, tillage and cover crop treatments existed concerning grain yield (Table 2, Fig. 4). In the plough treatment, averaged over years, wheat yield was the lowest in the no cover crop control (#8: 2.5 t/ha), and the highest for the field pea (#3: 3.4 t/ha). However, for each year taken independently, no significant pairwise differences between cover crop subtreatments could be highlighted. In the minimum tillage treatment, the same pattern was observed, with lowest yield in the no cover crop control (#8: 3.0 t/ha), and highest for the field pea (#3: 4.0 t/ha). All subtreatments led to yield higher than the no cover crop – plough reference treatment. Small differences were also observed within years (Fig. 4). In contrast, yield in the no till treatment varied importantly between cover crop subtreatments. The highest wheat yields were observed in the field pea (#3) and mixture (#7) subtreatments, in average and for all three years (Fig. 4). Average yield for field pea reached 3.3 t/ha (2.6 t/ha for the mixture), which made it comparable to the range of yields observed in the plough and minimum tillage treatments. This yield was clearly higher than that observed in the no cover crop – plough reference. However, mean wheat yield in the other cover crop subtreatments did not reach yield higher than 2 t/ha. In addition, for all cover crop subtreatments except field pea, yield decreased with time in the no till treatment, from 2014 to 2016, showing likely cumulated negative effects.

Wheat grain yield was generally correlated with cover crop (biomass, soil cover, N uptake, C/N ratio) and weed (biomass) status, but the specific characteristic showing the highest correlation with wheat yield differed between years and tillage treatments (Table 3). Wheat yield in the no till treatment showed higher correlation to these characteristics than in plough and minimum tillage treatments, showing a more important role for wheat yield of cover crop in no till systems compared to tilled ones. In 2014 and 2015, when cover crop biomass was generally low and highly variable between cover crop species, wheat yield correlation was the highest with cover crop biomass (minimum tillage and no till) or soil cover (plough). In contrast, in

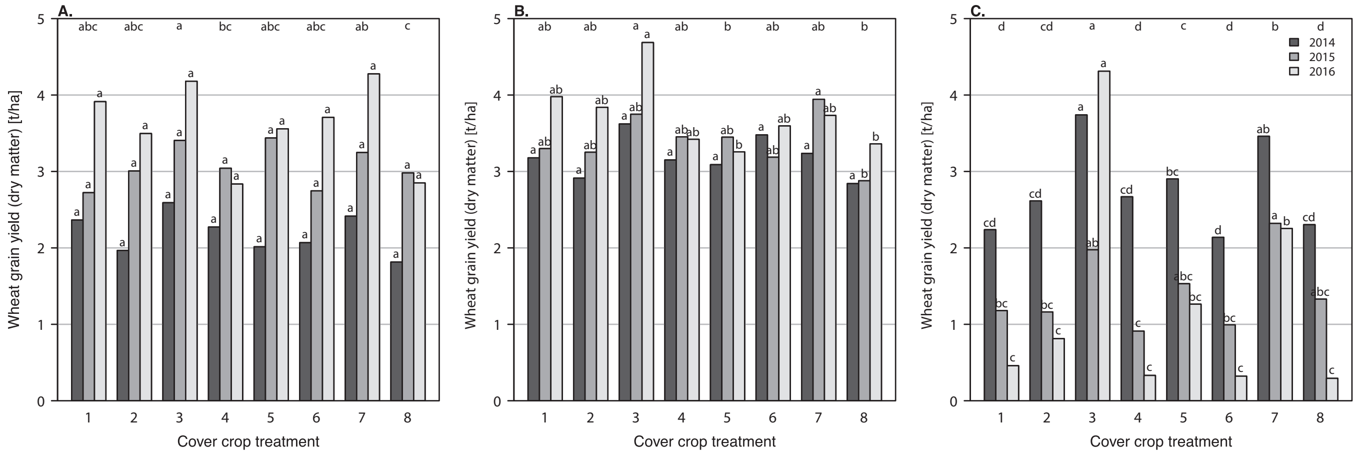

Fig. 4. Wheat grain yield [t/ha] in function of the cover crop treatments, for A. plough, B. minimum tillage and C. no till treatments. Cover crop treatments are 1. brown mustard, 2. daikon radish, 3. field pea, 4. black oat, 5. niger, 6. phacelia, 7. cover crop mixture, 8. no cover crop control. The bar colour represents the year of experiment, dark grey for 2014, grey for 2015 and light grey for 2016. Different letters (above each bar) show significant differences between cover crop treatments (tested independently for each tillage treatment and year). The letters at the top of each panel correspond to differences in mean wheat yield, computed over the three years.

Table 3
Coefficient of correlation between cover crop characteristics and wheat yield for each year and tillage treatment. The maximum value for each tillage x year is surrounded by stars (*…*). Significant values ($p < 0.05$) are in bold.

		Cover crop characteristics			
		biomass	soil cover	N uptake	C/N
2013–2014	plough	0.425	*0.433*	0.355	−0.335
	min till	***0.842***	**0.837**	**0.819**	**−0.717**
	no till	*0.416*	0.297	0.332	−0.238
2014–2015	plough	0.496	***0.521***	0.456	−0.292
	min till	***0.646***	**0.578**	**0.595**	−0.450
	no till	***0.675***	**0.642**	**0.559**	−0.459
2015–2016	plough	0.418	**0.603**	**0.592**	***−0.685***
	min till	0.414	**0.639**	***0.903***	**−0.867**
	no till	0.202	0.444	**0.590**	***−0.642***

2016, when cover crop biomass was generally higher, wheat yield correlated more with cover crop properties linked to nitrogen, such as C/N ratio (plough and minimum tillage) and N uptake (no till) (Table 3).

3.4. Total aboveground production and nutrient cycling

During these three years of experiment, additional measurements were done in the field pea and no cover crop control subtreatments. Total aboveground net primary production, i.e. the cumulated plant biomass grown from each plot during the whole experiment (cover crop, weeds, wheat grain and straw and stubbles), showed high differences between tillage and cover crop treatments (Fig. 5). Highest production was achieved in the minimum tillage with field pea, with up to 40.9 t/ha produced in three years. In contrast, the lowest production was observed in the no till no cover crop control, with only 13.7 t/ha total biomass produced. From that, 23.0 t/ha was exported from the field pea minimum tillage plots (wheat grain + straw), whereas only 8.1 t/ha was exported from the no till control plots. These amounts could be translated into C and N balance for each treatment (Fig. 6). Carbon inputs in the field pea plots were similar between tillage treatments, and reached about 18 t/ha cumulated over the three years. In contrast, they were more variable for the no cover crop plots, with about 13 t/ha with plough and minimum tillage and only 6 t/ha for no till. Once subtracted the exported part, C net input reached 5 t/ha for field pea plots and about 2 t/ha for the control plots (Fig. 6). Nitrogen inputs consisted in mineral fertilisers and potential N biological fixation by field pea. It reached 0.39 t/ha for the control plots (mineral fertilisers only) and about 0.6 t/ha for field pea plots. These represented net N inputs of about 0.24 t/ha for field pea plots and the control plot in no till (due to really low amount of exported N), and about 0.1 t/ha for the other two control plots (Fig. 6). Phosphorus P and potassium K were not brought as fertilisers during this experiment, and so only exportations occurred. For P, exportation was about 60 kg/ha for pea (all tillage treatments), 51 kg/ha for the no cover crop control (plough and minimum tillage) and 26 kg/ha for the control in no till. For K, exportation was about 178 kg/ha for pea (all tillage treatments), 150 kg/ha for the no cover crop control (plough and minimum tillage) and 56 kg/ha for the control in no till.

These differences in nutrient balance between pea and control translated into differences in nutrient concentration in the soil for some of the treatments in 2016, despite the short duration of this experiment (Fig. 7). As expected, no differences were observed for soil organic C. For nitrogen, the field pea plots in the minimum tillage treatments showed higher total N concentration than the control plots in the 0–20 cm layer. The same tendency was observable for the other tillage treatments but these differences were not significant. In contrast, for phosphorus P and potassium K, the tendency was to lower values in the field pea plots, due to higher amounts of exported biomass, through wheat grain and straw. This was particularly visible in the no till treatment, which showed the highest differences in exported amounts between field pea and control plots (Fig. 6).

3.5. DayCent model performance

DayCent was able to simulate soil organic carbon (C) dynamics under tillage treatments over the period 1969–2013 quite well (n = 90, RMSE = 3.67 t C/ha, rRMSE = 0.08, R^2 = 0.94 across the treatments). The model performance results on simulating the soil organic C dynamics, wheat, maize and rapeseed yields under the individual tillage treatments during this period are presented in Necpalova et al. (under review) (Supplementary Fig. S2). Following the additional calibration efforts to simulate field pea growth at this site, the model simulated its aboveground biomass across the tillage treatments and years satisfactorily (n = 18, RMSE = 0.21 t C/ha, rRMSE = 0.19; Supplementary Fig. S2). Mean simulated N fixation by field pea across the tillage treatments and calibration years (mean: 90 kg N/ha, min: 23, max: 149) was also very comparable with the values estimated in this experiment (mean: 71 kg N/ha, min: 37, max: 122), and those reported in Büchi et al. (2015) at the same site (mean: 115 kg N/ha). The positive effect of field pea on wheat yield in the three year experiment,

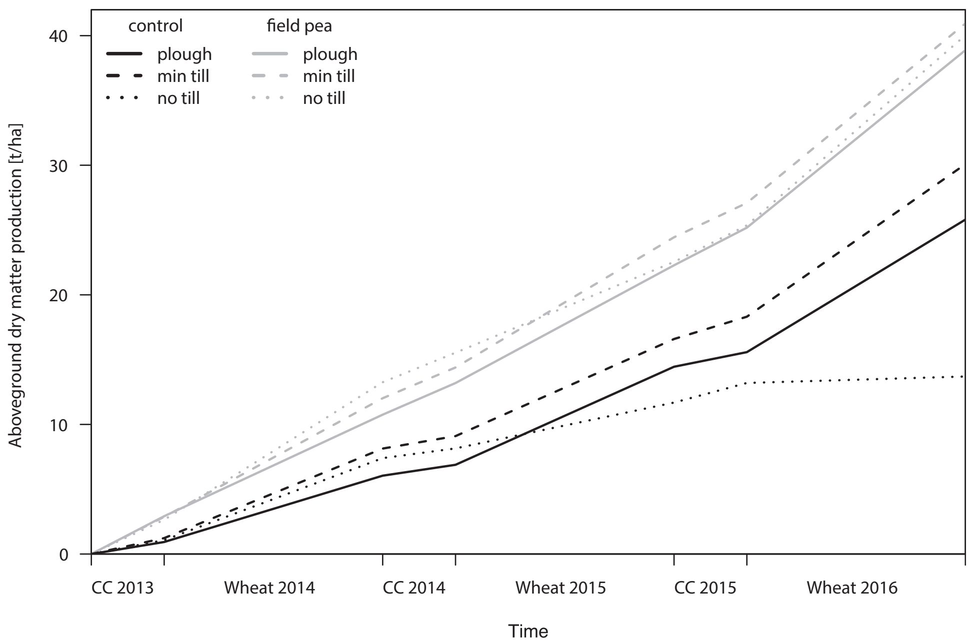

Fig. 5. Evolution through time of aboveground dry matter production (cover crops + weeds + wheat grain, straw and stubble) [t/ha] of the field pea and control plots, for all tillage treatments.

compared to the no cover crop control, also appeared in the simulated results (Supplementary Fig. S2).

3.6. Long term effects on soil C and N

The simulated scenarios showed a strong influence of field pea cover crop cultivation and tillage management on the evolution of soil organic C (Fig. 8) and total nitrogen stocks (0–20 cm) on the long term. In the absence of cover crops, soil organic C stock continued to decrease compared to the situation observed in 2012, i.e. last year before the start of the cover crop experiment (mean soil organic C stock in 2012: 48 t/ha), except for the no till treatment. Introducing cover crops, even only once every four years (scenario 1cc), allowed to increase soil organic C stock relative to the level observed in 2012. The maximal gain was observed in the no till treatment, with the 3cc scenario, with an increase of soil organic C stock of 15 t/ha in 55 years. This corresponded to an average annual increase of 0.28 t/ha/y. In this treatment, the annual increase ranged thus from 0.14 (1cc) to 0.28 (3cc), while it ranged from 0.09 (1cc) to 0.21 (3cc) in the minimum tillage treatment, and from 0.02 (1cc) to 0.1 (3cc) in the plough treatment.

Some of the simulated scenarios even allowed to return to, or even go over, the level of SOC observed at the beginning of the long term experiment in 1969 (mean soil organic C stock in 1969: 53 t/ha) (Fig. 8a). This was the case for all cover crops scenarios in reduced tillage treatments, but for no scenario in the plough treatment. As the minimum tillage treatment was the one showing the highest SOC values in 2012, it allowed to reach the initial soil organic C level from 1969 again the fastest, in around 2022 for '1cc', 2019 for '2cc' and 2017 for '3cc'. In the no till treatment, the initial 1969 value of soil organic C stock was reached again in around 2044 for '1cc', 2037 for '2cc' and 2031 for '3cc'. The same patterns were observed for total nitrogen.

The increase in soil organic C stock was directly linked to the amount of C input (i.e., aboveground and belowground crop residues) provided to the soil (Fig. 8b). However, the rate of the increase

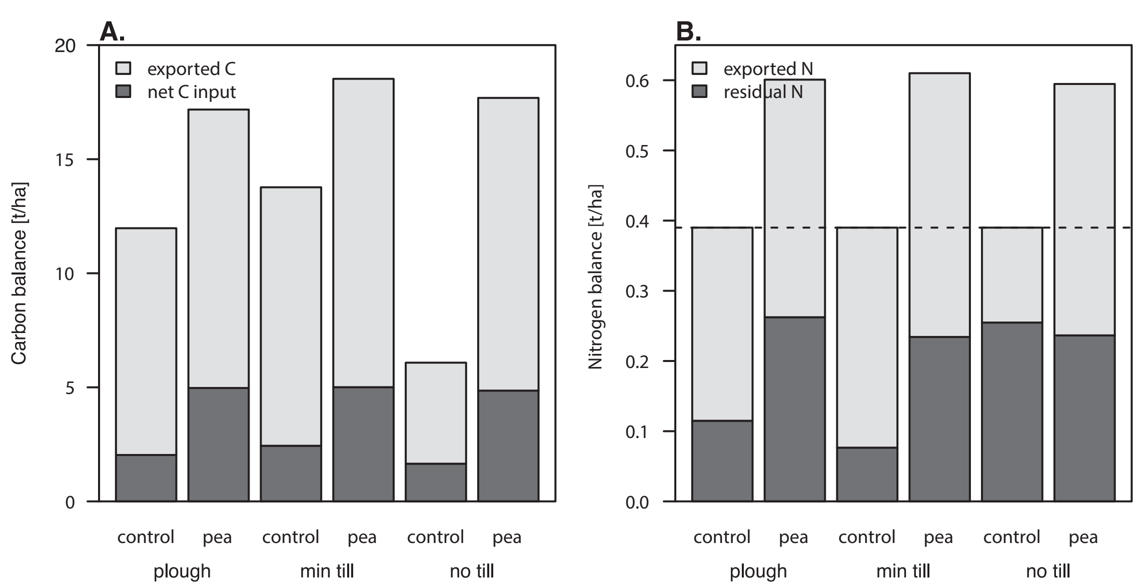

Fig. 6. Carbon (A.) and nitrogen (B.) balance for field pea and control plots, for all tillage treatments. The whole bars represent C and N inputs, whereas the light grey part correspond to the exported part. The difference (dark grey part) is the net input of C and N in the system. The horizontal dashed line in panel B represents the N fertiliser input.

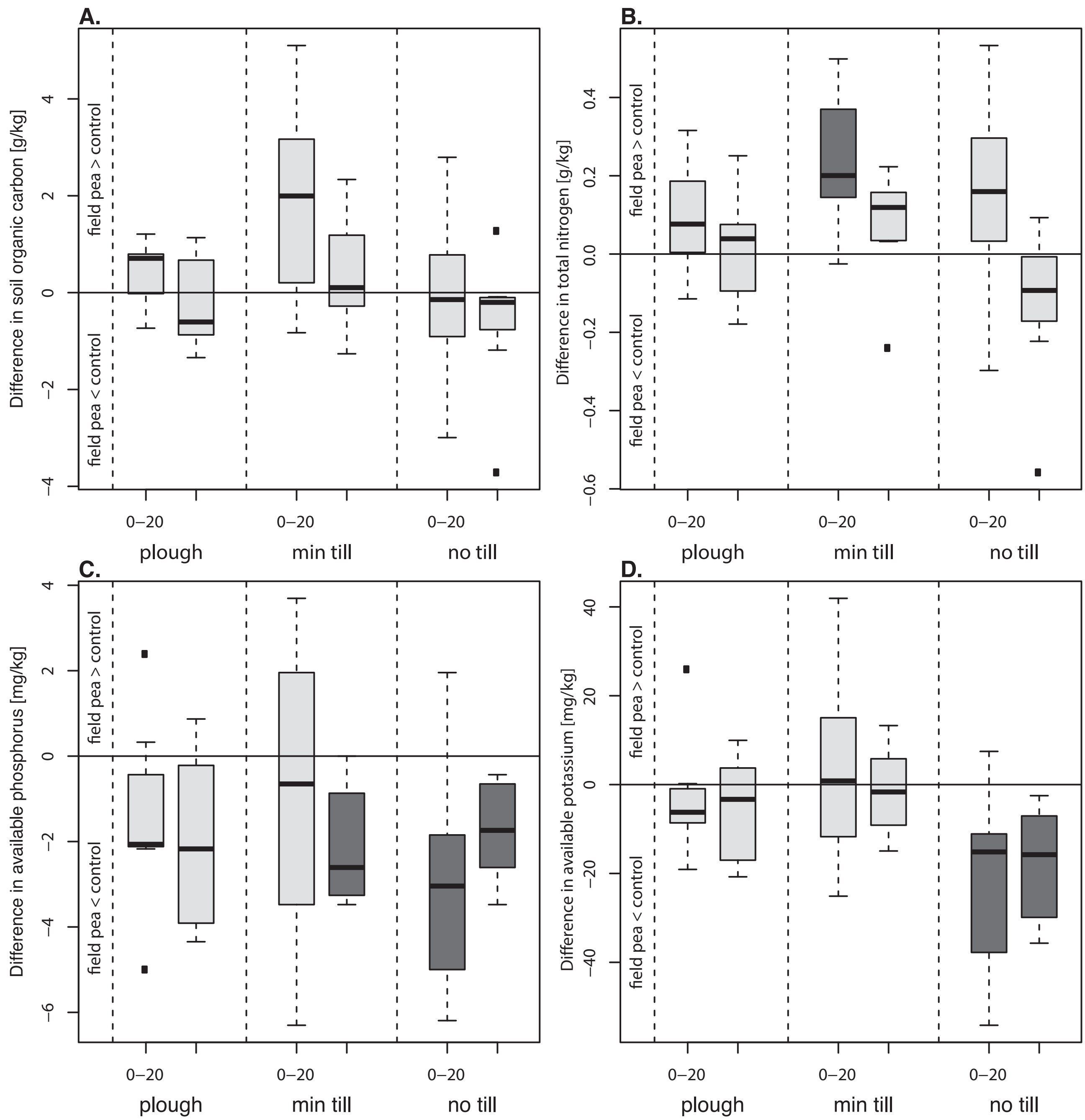

Fig. 7. Difference in organic carbon and nutrient concentration between field pea and control plots, in function of depth and tillage treatments, for A. soil organic carbon, B. total nitrogen, C. available phosphorus and D. available potassium. Differences significantly different from zero (paired *t*-test, $p < 0.5$) are shown in dark grey. Each box represents the distribution of $n = 7$ values, corresponding to the seven replicates of this experiment.

depended on the tillage treatments. In the reduced tillage treatments, the gain of soil organic C for a given amount of C input was higher than in the plough treatment.

4. Discussion

4.1. Cover crops and weeds

Our results showed important differences in cover crop growth depending on the species and on the year of cultivation. The effect of tillage treatment was less marked, but this could be explained by the fact that all cover crops were seeded directly in summer, the last tillage operations dating back to previous fall. The differences observed were thus indirect effects of tillage treatments. Indeed, this experiment was set up within a long term experiment on soil tillage, in which more than 40 years of differentiated practices have modified soil properties (Büchi et al., 2017). Cover crop biomass production in this experiment was globally very low, except in the last year. For the two first years (2013 and 2014), only field pea and the mixture allowed to reach 3 t/ha, which is the average biomass production observed at this site (Wendling, 2017). In 2015, higher precipitation and growing degree days allowed almost all species to produce sufficient biomass. Comparisons with the biomass produced by the same cover crop species in other field experiments set up in the same years and in the same site (Wendling et al., 2016, Wendling, 2017) give interesting insights. For the two first years, cover crop biomass in the present experiment was around 10% of that observed in the other experiments (except for pea and the mixture). In contrast, the last year, cover crops reached 60% to

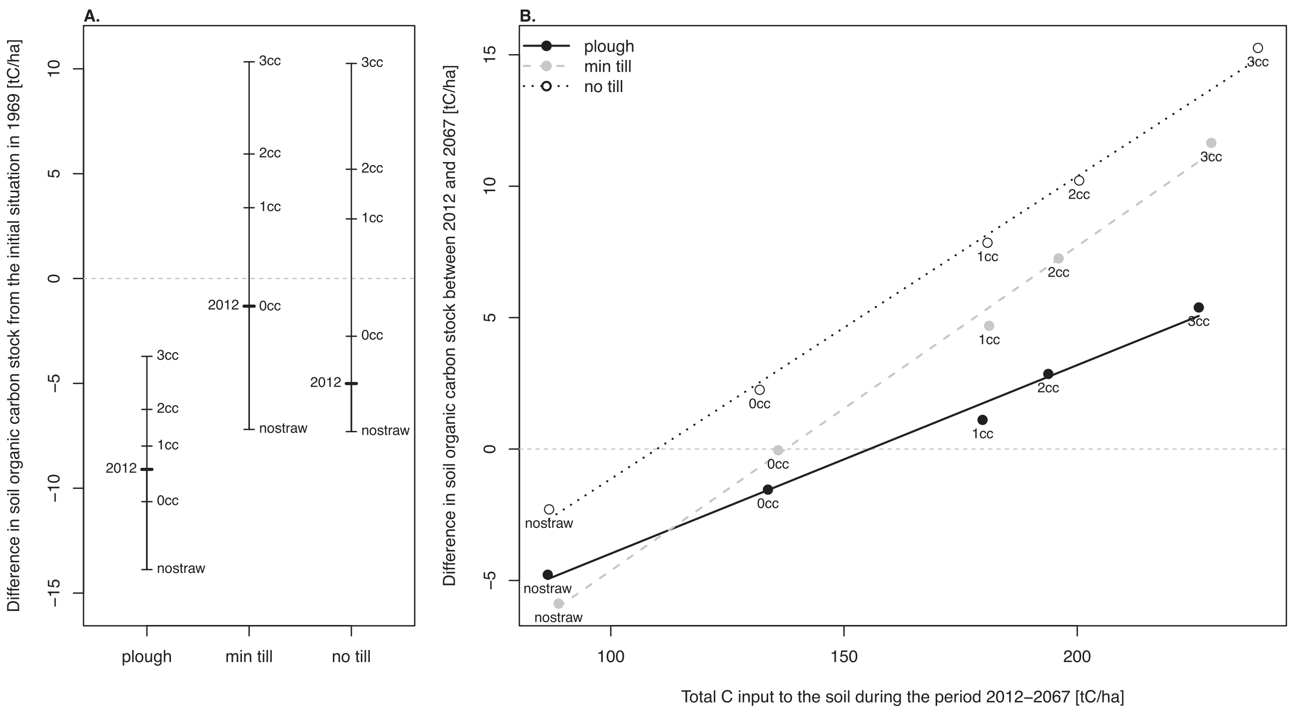

Fig. 8. Differences in soil organic carbon stock according to the different scenarios simulated. A. differences between the initial stock in 1969 and the stock in 2067, the situation in 2012 is represented by a bold line, B. relationship between differences in soil organic carbon stock and the mean carbon inputs for the period 2012–2067. Linear regression slopes are 0.072 for plough treatment, 0.123 for minimum tillage and 0.115 for no till. Carbon stocks for the different scenarios were compared in 2067. Scenarios: '0cc' – no cover crops, '1cc' – 1 cover crop in the four year rotation, '2cc' – 2 cover crops in the four year rotation, '3cc' – 3 cover crop in the four year rotation, 'nostraw' – no cover crops, and wheat straw exported, while it is left on the field in all other scenarios.

100% of the biomass observed in the other trials. The main difference between the present experiment and the other ones was that in the latter, the soil was tilled before cover crop seeding. This shows that tillage prior to cover crop seeding is a major factor allowing to counterbalance adverse biotic (e.g. weed pressure) or abiotic (e.g. low available N) stresses, as differences in biomass production between no till and tilled fields was the highest in the two first years. This effect is likely due to the increased mineralisation and improvement of seedbed induced by tillage (Six et al., 2002). In this context, field pea was a notable exception. Its biomass production did not vary much among the three years (2–3 t/ha), and represented up to 80% of the biomass observed in other trials, but was thus non responsive to the betterment of growing conditions the last year. The mixture also produced high biomass the three years of experiment. However, its specific composition changed with years, with clear dominance of legume species the two first years. Altogether, these results showed that legumes were far better adapted to harsh weather conditions and low mineralisation and nitrogen availability encountered in our experiment. This could be explained by the capacity of legumes to fix nitrogen from the atmosphere and thus to be less dependent on soil nutrient availability. A second factor could also play a role here. Indeed, another characteristic of the legume species was that they had rather big seeds, compared to the other species. This implies higher nutrient reserve at the beginning of seed development, which can be an advantage in this kind of conditions, though big seeds generally require higher humidity to germinate (Tribouillois et al., 2016). One observation supported this hypothesis, as in the mixture, sunflower, which also has rather big seeds but is not a legume, thrived the three years despite low seeding density. These results demonstrated that the choice of the cover crop species is crucial, and must be done consciously according to the aims and constraints of cover crop cultivation.

These differences in cover crop performance translated into different ability of cover crops to compete against weeds. In this experiment, application of glyphosate after wheat harvest in 2014 and 2015 reduced weed pressure by living weeds. So cover crops played a role especially against new germinating weeds, preventing their emergence or growth. As expected, high biomass production allowed a better weed control, but soil cover appeared to be a better predictor of cover crop ability to compete against weeds, probably due to increase in light competition. Cover crops presenting a creeping vegetation, like field pea, offer a better soil cover for a same biomass than erected cover crops, and decrease weed biomass more efficiently. In the no till treatment, weed pressure clearly increased with time, due to cumulated negative effects of low cover crop biomass, absence of tillage and low wheat yield. This negative spiral was avoided only in the field pea treatments, which offered stable and sufficient soil cover.

Weed control in reduced tillage systems is a major issue preventing wider adoption of these practices (Melander et al., 2013). Strict no till systems currently rely massively on the use of glyphosate, with high risk of resistance appearance and environment pollution (Délye et al., 2013; Powles, 2008). Reducing tillage in organic systems is thus a current challenge, for which cover crops have been shown to be central (Clark et al., 2017; Mirsky et al., 2013). In this experiment, high infestation of rattail fescue (*Vulpia myuros*) rendered necessary the application of glyphosate after wheat harvest, however with low overall success. This grass species is increasingly found in no till or minimum tillage cropping systems, all over the world, from USA to Europe and Australia (Ball et al., 2007; Mathiassen et al., 2010). Its huge seed production, ability to produce dense and competitive carpets of plants and resistance to some herbicides contribute to its thriving in no till fields (Ball et al., 2008; Jemmett et al., 2008; Lawrence and Burke, 2014). For these reasons, the spread of this species should surely be monitored more attentively if major problems in no till systems want to be avoided in the near future.

4.2. Effect on the following wheat crop

Wheat grain yield was globally low in this experiment, due to bad seeding conditions in the first year, bad weather conditions in spring of year 2014, and to the succession of wheat cultivation in general. Wheat grain yield showed high response to tillage and cover crop treatments. Interestingly, in this experiment, the highest yield was observed in the minimum tillage treatment which presented yield systematically higher than in the plough treatment. The no till treatment was clearly unsuccessful as a whole. However, the field pea treatment in the no till treatment allowed to reach wheat yield similar to those observed in the other tillage treatments, and, in particular, higher than in the classical plough – no cover crop control treatment. So, the presence of a good soil cover before wheat cultivation, even for a short period (only two months here) allowed to alleviate the detrimental effects of tillage reduction. In tilled treatments, the positive effect of cover crop cultivation was less pronounced, though visible when looking at the whole three year period. This agrees with other studies showing a more important role of cover crops with reduction of tillage intensity (Abdollahi and Munkholm, 2014; Wittwer et al., 2017). Many factors can explain the beneficial effect of cover crops for the next crop; among these are the reduction of weed pressure, improvement of soil fertility and soil quality, and nutrient release during decomposition (Abdollahi and Munkholm, 2014; Fageria et al., 2005; Mat Hassan et al., 2013; Thorup-Kristensen et al., 2003). These different mechanisms are difficult to disentangle, and can also all be present together and interact. When looking at the correlation between wheat yield and cover crop characteristics, differences between years appeared. The first and second years, when cover crop growth was really low, wheat yield was correlated with cover crop biomass and soil cover, though it was significant only for no till in the first year. The third year, when all cover crop grew reasonably well, wheat yield showed the highest correlations with characteristics linked to nitrogen, i.e. N uptake and C/N ratio. The relative weights of the different mechanisms involved in cover crop beneficial effects are thus likely to change according to cultivation conditions. Here it seemed that the first important condition to insure good wheat yield was that the cover crop produced sufficient biomass or cover. Then when this aspect was ensured, nitrogen availability played a major role for the next wheat. Interestingly, wheat yield in no till plots with the mixture as previous crop was lower in 2016, and notably lower than in field pea plots, despite a really high production of biomass by the mixture this year. Too high biomass could have prevented the good emergence of wheat at seeding, or biomass decomposition in spring could have induced nitrogen immobilisation, due to high C/N ratio, linked to the lower proportion of legumes observed this year. These are two negative aspects of cover crop cultivation often mentioned in this context (Dabney et al., 1996; Fageria et al., 2005). Producing the highest possible cover crop biomass is thus not necessarily the objective in such systems. In addition, the use of cover crop mixtures, while offering the advantage of multiple ecosystem services at the same time, have less predictable outcomes due to potential changes in species composition in response to environmental conditions.

4.3. Consequences for soil fertility

To assess total net biomass production, belowground production should also be taken into account, as it has been shown that root derived carbon (C) is even more important for soil fertility than aboveground residue C (Kong and Six, 2010). However, we lacked here information to estimate it accurately. Compared to the reference treatment, plough with no cover crop, the treatments involving field pea as cover crop showed total aboveground production values representing around 155% of this reference treatment, even in the no till treatment. In contrast, no till with no cover crop reached only 53% of this reference value. These differences were very large and could have strong environmental repercussions. For example, soil fertility, and especially soil organic C content, is fundamentally dependent on the amount of C inputs provided (Autret et al., 2016; Virto et al., 2012), which was also confirmed here by the results from the long term simulations. Maintaining soil fertility on the long term on a sustainable basis is the major challenge of agriculture nowadays, especially with the development of biofuel production, consuming huge amounts of crop residues. Cover crop cultivation, and especially legumes, has been shown here to be an efficient way to increase total production, and thus C inputs. This was not directly translated into significant increase of soil organic C content, but this experiment lasted only three years. Differences in soil C after only three years have however been observed in the study of Hubbard et al. (2013). In contrast, differences were observed for total soil nitrogen in the minimum tillage treatments, with higher values in the field pea compared to the control treatment.

The complementary long term simulations showed that 50 years of regular cover crop cultivation could drastically increase soil organic C and total nitrogen, and counterbalance the negative effect of ploughing. Coupled with reduced tillage, cover crops even allowed to reach C stocks similar or even higher than what was observed at the beginning of the experiment in 1969. This is in accordance with many studies which have demonstrated the beneficial effects of cover crop on soil fertility and quality (e.g. Abdollahi and Munkholm, 2014; Mazzoncini et al., 2011; Mitchell et al., 2017; Sainju et al., 2002; Sapkota et al., 2012). The average annual soil organic C stock change observed in our simulations (from 0.02 to 0.28 t/ha) was similar to what has been reported by Poeplau and Don (2015) based on an extensive meta-analysis of cover crop field experiments. They found an annual change rate of soil organic C stock of 0.32 t/ha for 22 cm depth, in 54 years. However, their study did not reveal any significant influence of soil tillage on these values, in contrast to what has been shown here. The potential for total soil organic C stock increase thanks to cover crop cultivation is thus substantial, and could play an important role in C sequestration and non-permanent greenhouse gas emission mitigation (Kaye and Quemada, 2017; Poeplau and Don, 2015). In addition, here the simulations showed that after 50 years, SOC did not reach an equilibrium and was still steadily increasing. However, although the results obtained with DayCent allowed to represent well grain yield, the model tended to overestimate yield due to the lack of integration of biotic processes such as weed, pest and disease incidence, crop failure due to unsuitable seedbed, etc. This could have an influence on C input estimation, especially in the reduced tillage treatments.

In addition to soil fertility, cover crops also play a role in nutrient recycling, modifying their cycle and timing of availability (Fageria et al., 2005; Mat Hassan et al., 2013). This is especially the case of legume species, which contribute to net inputs of nitrogen in the system through biological fixation. Biological fixation by legume cover crops could bring really high quantities of nitrogen even when cultivated for a short period, more than 100 kg N/ha according to a study conducted in the same site (Büchi et al., 2015). Here, estimations of biologically fixed nitrogen amounts for field pea were a bit lower, due to lower biomass production, but total N uptake of field pea was still around 100 kg N/ha. Such high amounts of N uptake should be sufficient to allow for a reduction of the successive main crop fertilisation. Indeed, Tonitto et al. (2006) have shown, in a meta-analysis, that, when legumes accumulated more than 110 kg N/ha (biological fixation + soil uptake), the yield of the following crop reached, in the absence of mineral fertilisation, yield similar to fertilised crops. This aspect could however not been tested in this experiment and should be the object of further investigations. Legume species have also been shown to have a positive effect on phosphorus mobilisation and contribute to phosphorus uptake of the following crop (Espinosa et al., 2017; Mat Hassan et al., 2013; Nuruzzaman et al., 2005). Cover crop cultivation has thus many benefits in agroecosystems and can contribute to a decreased reliance on mineral fertilisers and alleviation of environmental impact. In this study, the best cover crop – tillage combination, in terms of yield, appeared to be field pea with minimum tillage. This combination allowed to combine the beneficial effects of the legume cover crop and reduction of soil tillage compared to plough. In contrast, even if field pea with no till led to reasonable wheat yields, the no till treatment suffered from higher yield variability and practical management issues (especially weed control). Reduction of tillage intensity allows, among others, improving soil quality and reducing labour and fuel costs (Holland, 2004; Soane et al., 2012). The better weed control observed in this treatment should also allow to reduce herbicide use in the future, though here all treatments received the same herbicide applications. This combination appeared thus, in addition of being currently the most successful, also to be promising for an increased sustainability of the agroecosystem, especially in face of global changes. The soil protection provided by cover crops, together with reduced soil tillage, plays an important role against soil erosion, an environmental hazard likely to be more problematic with the increasing frequency of extreme meteorological events like heavy rain and hail. Also the higher success of big legume seeds in germinating in dry and hot summer conditions, and their higher amount of nutrient reserve which renders them less sensitive to initial soil nutrient availability, could turn to be an advantage in a changing future.

5. Conclusions

This experiment has shown that cover crops play a crucial role in reduced tillage systems, and especially with no till. Cover crops developing a sufficient amount of biomass before the seeding of the main crop allow to compete efficiently against weeds. In addition, cover crop cultivation increases carbon inputs to soil and soil organic carbon stock on the long term. This thus sustains soil fertility and nutrient cycling, and could play an important role in non-permanent greenhouse gas emissions mitigation. With no till, field pea grown as a cover crop before winter wheat allowed to reach grain yield similar to those observed in the tilled treatments. However, when cover crops did not grow well the system performed poorly, with high weed pressure, low wheat grain yield, in a cumulated negative effect loop. The best combination appeared to be field pea cultivation in the minimum tillage system. These findings have important repercussions for the environment as many ecosystem services are related to cover crop cultivation and reduction of soil tillage, e.g. increased soil fertility, prevention of soil erosion, reduction of nutrient leaching and of field traffic and fuel cost. This also advocated for a more general adoption of conservation agriculture principles, in order to build innovative and sustainable cropping systems for the future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2018.01.005.

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