Synthesis of a 47-year old field experiment in France, comparing soil tillage techniques in different crop rotations

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Picture comment: The soil tillage experiment area ranged from 11 ha in 1971 to 5.5 ha in 2017.

Objectives of the long-term experiment

Several soil tillage field experiments have been carried out by Arvalis from the 70's to recently. The oldest one was established in Boigneville (in Essonne, 70 km south of Paris) in 1970. It is still on-going. The experiment has however strongly changed in its objectives and treatments since 2018. So, we will consider in this paper the results from the initial objectives, including harvest 1971 to 2017.

The initial objectives of the experiment were to assess the impact of minimum tillage or no till on crop establishment and measure their impacts on crop yield components, pests, physical and chemical soil parameters in the long term.

Partnerships have been crucial for this experiment. ITB was strongly involved in the monitoring of sugar beet. INRA, AgroParisTech and several universities conducted many soil measurements: physical, chemical, biological properties, greenhouse gas emissions.

Site description and experimental design

The climate is temperate oceanic, with an average temperature of 11.0°C and rainfall of 635 mm per year. The orthic luvisol is developed on loess (table 1). It has a good drainage, an average structural stability and a good ability to crack when it dries in summer.

Table 1: Soil description. The texture was obtained without preliminary decarbonation.

Depth	Description	% clay	% silt	% sand	Total $CaCO_3$	% OM	pH in water
0-30 cm	No stone, polyedral structure	24	67	9	<1%	1.9	7.1
30-80 cm	No stone, prismatic structure	32	64	4	<1%	1.2	7.6
80-120 cm	Few roots	25	51	24	31	1.1	8.3
>120 cm	Hard limestone						

Picture comment: Soil profile on a ploughed plot, from the surface to 1.0 m depth.

Four experiments were set up in 1970, each with its own crop rotation (table 2):
- Experiment D: Continuous maize without irrigation, from harvest 1971 to 1994.
- Experiment C: Continuous winter wheat without irrigation from 1971 to 2009. In order to manage a high rye grass population, wheat was destroyed in 2010 and a crop rotation was introduced until 2016.
- Experiment B: Maize-winter wheat rotation with irrigation from 1971 to 1983.
- Experiment A: Maize-winter wheat rotation without irrigation from 1971 to 1997. Each crop was present each year on four replicates. From 1998 to 2017, on half of this experiment

(experiment A1), irrigation was applied to maize. Each crop was present every year with two replicates. Another rotation was carried out in the other half of the experiment (A2): sugar beet - winter wheat - spring pea or winter faba bean or oilseed rape - spring barley. Irrigation was applied only to spring crops, mainly sugar beet. In this A2 experiment, the four crops of the rotation were established each year but with only one replicate.

For each crop rotation, three to five soil tillage techniques are compared. We had as a minimum conventional tillage (CT, 20 cm depth annual ploughed based system), superficial tillage (ST, 5 to 10 cm depth) and no till (NT). Sometimes, there can be an additional superficial tillage technique (STbis) and a minimum tillage (NTbis, including no till or superficial tillage or strip tillage depending on the period and the crop). The soil tillage techniques are described in detail later in this paper.

Cover crops were introduced in the A1 experiment, between wheat and maize from summer 2001 to 2014. Each plot was divided into two parts with or without cover crops, the soil tillage remaining unchanged. Volunteers and weeds on bare soils were usually destroyed in September either chemically or with one additional mechanical operation. Since summer 2015, cover crops were established in the entire plots. They were sown in early September from 2001 to 2007, and then sown earlier, in August. The species were oats at the beginning, then oat with leguminous crops and since 2013 a mixture of mustard, phacelia and leguminous crops. They were destroyed at two different periods: autumn for CT, ST and NT (mid-November to mid-December); late winter for STbis and NTbis (late February to early April). The cover crop biomass at their destruction period was on average of 1.2 t DM/ha in autumn and 1.9 tDM/ha in winter. Most years, this biomass was not very significant, due to having been established in difficult conditions (straw in the seedbed, lack of water), slug attacks, and lack of available mineral nitrogen…

In A2 experiment, cover crops were introduced in the summer of 2008, in the entire plots. They were sown before barley and sugar beets. They were sown in August after the harvest of faba bean or barley. The annual species established were often a mixture of mustard, phacelia and leguminous crops As the preceding crop was oilseed rape, the cover crops were perennial species (mainly white clover), sown with this crop. The objective was to produce a well-developed leguminous cover crop after the oilseed rape harvest.

Table 2: Description of the five crop rotations. WW: winter soft wheat (rarely replaced by spring wheat or barley); SBe: sugar beets; LEG: spring pea or winter faba bean; OSR: oilseed rape; SBa: spring barley. The year cover crops are sown (e.g. 2001) proceed the year crops are harvested (e.g. maize in 2002).

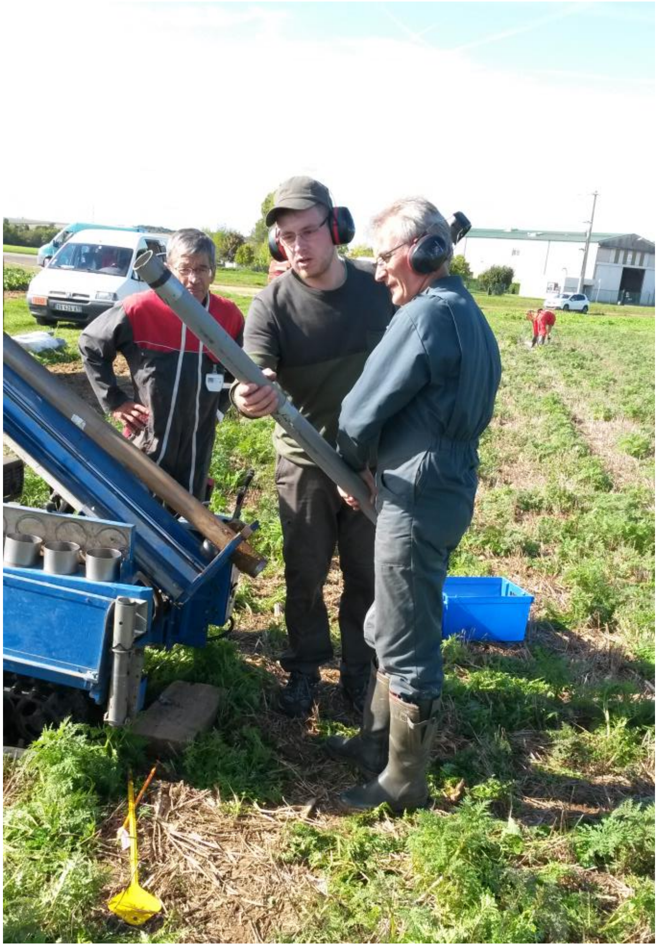
Experiment	Duration	Crops	Design	Treatments
A and A1	1971-2017	Maize-WW (maize irrigated since 1998)	Split-plot 4 replicates for each crop (2 since 1998) Plot size : 800 m2 (400 m2 since 2000)	**10 treatments:** 5 soil tillage techniques (wheat straw and maize residues were removed on some plots from summer 1982 to 1993) x 2 cover crop treatments from summer 2001 to 2014 (with or without cover crop). There was no cover crop on each plot before 2000 and there was a cover crop on each plot since 2015.
A2	1998-2017 (experiment A from 1971 to 1997)	SBe-WW-LEG or OSR-SBa (spring crops irrigated)	1 replicate for each crop Plot size : 800 m2	5 soil tillage techniques
B	1971-1983	Maize-WW (maize irrigated)	Split-plot 4 replicates for each crop Plot size : 800 m2	5 soil tillage techniques
C	1971-2016	Continuous WW from 1971 to 2010 (crop rotation after: LEG-OSR-WW-SBa-Maize-WW).	1 replicate for one crop Plot size : 1760 m2	**6 treatments:** 3 soil tillage techniques x 2 fungicide treatments (with or without since 1974)
D	1971-1994	Continuous maize (non irrigated)	1 replicate Plot size : 1760 m2	3 soil tillage techniques

In this long term experiment, practices were repeated every year in the same plots. For example, some plots were ploughed every year. Some others were not tilled since 1970.

The objectives of the field experiment were to compare the impact of different practices such as soil tillage, cover crops, crop rotation… all other practices being the same. For example, regardless of what the soil tillage was, the crop variety, the sowing day, the fertilization and the crop protection were the same. Plots were managed so as not to create limiting factors. Herbicides were managed in order to destroy weeds in plots where they were the most numerous. The exception was glyphosate that was not sprayed on bare soils without weeds. The field experiment we present here is an analytical experiment and not a cropping system experiment. In our case, we compare different techniques and the difference observed between treatments can be connected to a practice (e.g. ploughing versus direct drilling). In a cropping system experiment, different systems are compared (e.g. conventional farming versus conservation agriculture). The results cannot be linked to a factor such as soil tillage but to the entire cropping system (including all its practices and the decision making).

Many measurements have been made in this experiment on the crops behavior (yield components, protein content of cereals, wheat diseases and sanitary quality, weeds…). Soil has also been monitored, frequently in collaboration with INRA (soil profile, soil moisture, biological activity, soil organic C, greenhouse gas emission…). From 1970 to 2017, soil density and carbon and nitrogen concentrations were measured almost every four years at different depths. The sampling methodology is described later in this paper. It allowed calculating soil organic carbon stocks on the basis of equivalent soil mass.

For an economical assessment, the net margin has been calculated for each crop rotation and each soil tillage: yield*price + subsidies - inputs - cost of mechanization - cost of hired or family labor - cost of irrigation - farm rent - national insurance contribution - miscellaneous expenditures - return on equity. Margin has been calculated on the basis of practices and yields measured each year on each plot. Price of grain and input are an average over the 2010-2016 period. Usually, input has not been different between soil tillage strategies, except for glyphosate. We consider that the number of labor units was the same regardless of the soil tillage strategy. That means that the labor cost was the same in spite of differences on the time spent on the tractor. Subsidies are calculated on the basis of 2017. A positive net margin with our calculation method means that all factors of production are paid for (land, asset, family labor). However, our calculation sometimes gives a rather negative margin because of old technical data (yield, practices) with current prices and subsidies.



Picture comment: Arvalis and INRA measured soil carbon in all plots from 1970 to 2017. 3 400 soil samples were analyzed and are still stored at Boigneville and INRA Laon.

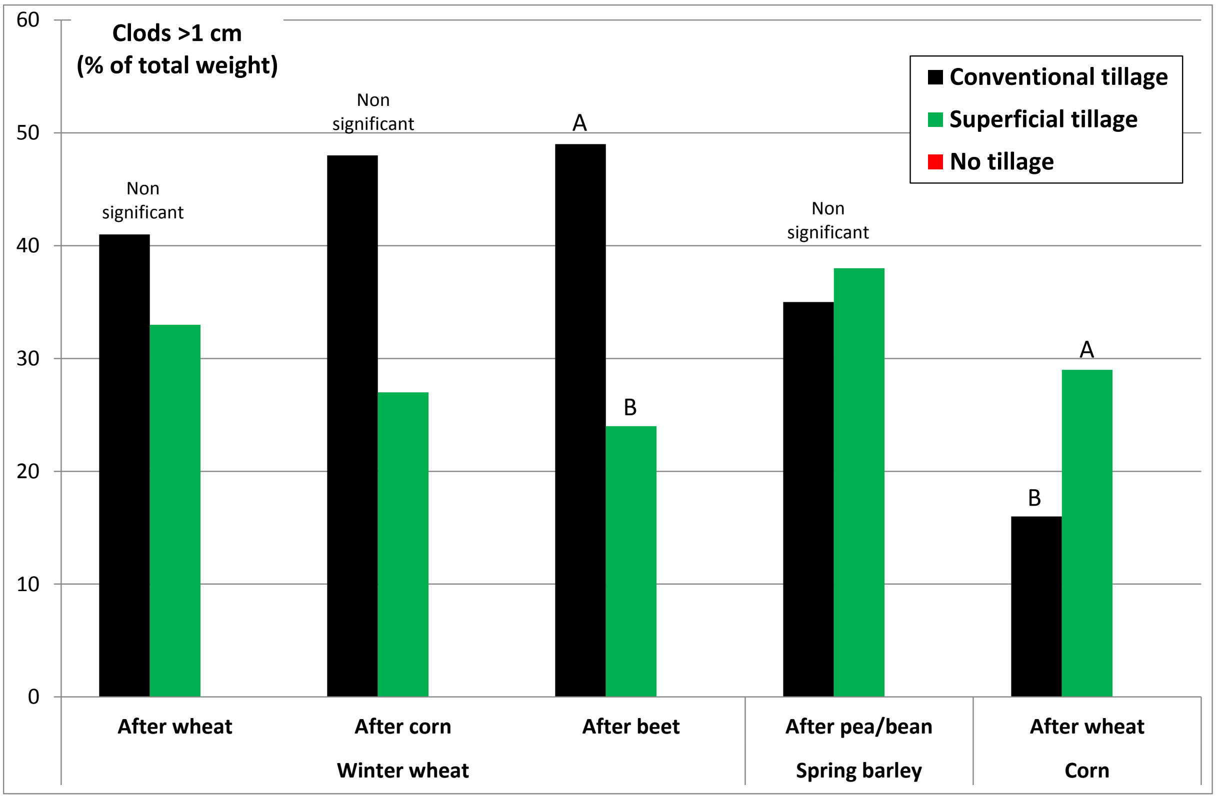
<u>Cloddiness of the seedbed</u>

One of the main functions of soil tillage is the creation of an appropriate seedbed for the crops. The cloddiness of the seedbed was measured several times by weighting clods of several size classes in the seedbed. It was not measured in direct drilling plots because the seedbed for this technique is limited to the sowing furrow. We present in figure 1 a synthesis of 6 years of data for different crops. In autumn for wheat, the seedbed tended to be coarser on ploughed plots. The clods size was quite equivalent with minimum tillage for spring barley and finer for maize. Ploughing occurred just before sowing for wheat and late November before spring crops. The period ploughed lands were exposed to the weather seems to explain the difference of cloddiness of inverted soils. This is one of the reasons for which farmers plough usually before spring crops and less often before autumn crops in our type of soil.

It is noticeable that cover crops did not have an impact on clods size before maize establishment, on ploughed plots late November after the cover crop or on minimum tillage plots, shallow cultivation being done before or after winter.

The crop emergence is presented below in this document (table 3). It was not possible to find a correlation with the cloddiness of the seedbed. The main problems on crop emergence were observed mainly on direct drilling techniques (NT) in a few cases: maize (problem: crows); sugar beet (problem: seed to soil contact, seed furrow closure); oilseed rape (seeding depth too shallow due to very dry soil one every four years); spring barley after oil seed rape with a cover crop of OSR volunteers and white clover (problem not well understood: very dense network of white clover stems of the soil surface that could have limited to seed furrow closure, difficulty to kill chemically the white clover that could compete with the barley seedlings). Except for these four examples, no till, min till or strip till gave on average crop emergence close to the ploughed soils, in spite of very different seedbeds. Indeed, many factors have an impact on emergence such as the seed to soil contact which is influenced by cloddiness as well as straw in the seedbed, the soil moisture, the closing of the seed furrow in the case of direct drilling and the impact of pests (slugs, crows…).

Figure 1: Impact of soil tillage on clods in the seedbed. Data for 6 years (crops harvested from 2005 to 2010).



Crop yield and net margin according to soil tillage and crop rotation

Average crop yields are shown in table 3. Anova have been made only if the experimental design includes several replicates. In most cases, yields were very close between CT, ST and NT. There are some exceptions:

- Wheat after wheat (straw chopped and spread): yields were lower in ST and NT of 0.7 t/ha as compared to CT. The number of ears, ear fertility and the weight of 1000 grains explain that. The causes were not well identified as it could be due to a higher pest pressure (rye grass, yellow leaf spot *Dreschlera tritici-repentis*) in ST and NT. As compared to straw burning, straw chopped in ST and NT could have led to a nitrogen deficiency.
- Wheat after maize: we did not see any difference in yield except on NT after the introduction of irrigation on maize. The amount of maize residues became very large, particularly along the maize rows. Wheat can hardly develop well in this case. Straw chopping after wheat direct seeding was found to be a solution (NTbis). Chopping helped to have a more even distribution of maize straw then of a wheat crop. It also reduced the deoxynivalenol content on wheat grain. In other cases, wheat yield was the same between CT, ST and NT.
- Maize yield was usually the same between CT and ST. We however had a significant yield increase on ST from 2014 to 2017 as the cultivation became deeper (10 cm instead of 5 cm), which could have improved maize rooting. Before 2001, NT was based on a PTO driven strip till. Emergence and yields were the same as CT. Since 2001, NT became a "real" no till plot. Maize emergence was then quite the same as CT or ST but since 2012, birds (crows) became a problem for NT maize emergence. During the 2001-2017 period, NT had the same yield as CT but there was a yield gap of approximately 1 t/ha since 2012.
- Sugar beets yielded the best on average on CT, as compared to ST and NT. The soil coverage by beets occurred earlier on CT and it seemed to explain the yield difference. In 2012, strip tillage was introduced in NTbis. It has been fully successful for beet emergence and yield. It has been the only tillage technique without soil inversion that performed as well as a ploughing technique.
- Spring pea yield was also better on CT than in min or no till. Crop emergence did not explain yield gap. In our field experiment, there could have been some trouble with pea roots or nodules without soil tillage deeper than 5 cm.

Table 3: Crop emergence (%), yield (t/ha) and net margin (€/ha) according to soil tillage technique, crop and preceding crop. For A1 experiment, anova results are in brackets (NS: p value > 0.10; .: p value <0.10; *: p value<0.05; **: p value<0.01; ***: p value<0.001). Results are compared to CT. Colors help to analyze net margin (in red: <-100 €/ha compared to CT; orange: -100 à -51 €/ha; yellow: -50 à -26 €/ha; white: -25 to +25 €/ha; apple green: +26 à +50 €/ha; dark green: >+50 €/ha).

Experiment	Crop / Preceding crop	Harvest year	Conventionnal Tillage (CT)	Superficial Tillage (ST)	No Tillage (NT)	NT or ST or Strip tillage (NTbis)
C	Winter wheat / Winter wheat (straw burnt)	1977-2001	PL, HA, SD 79 %, 7.54 t/ha, 217 €/ha	Rotavator, DD 85 %, 7.54 t/ha, 219 €/ha	No till, DDSD 85 %, 7.69 t/ha, 240 €/ha	
C	Winter wheat / Winter wheat (straw chopped)	2002-2009	SC, PL, RH, SD 68 %, 6.89 t/ha, 130 €/ha	SC, RH or Rotavator, DD 70 %, 6.21 t/ha, 60 €/ha	Spring tine harrow*2, DDSD 67 %, 6.22 t/ha, 73 €/ha	
C	Rotation	2010-2016	SC, PL, RH, SD /, /, 21 €/ha	SC, DD /, /, 21 €/ha	No till, DDSD /, /, 9 €/ha	
D	Maize (non irrigated) / Maize (straw chopped)	1987-1994	PL, HA, Vb, SD 89 %, 5.85 t/ha, -401 €/ha	Stubble plough, HA, Vb, SD 92 %, 5.96 t/ha, -405 €/ha	PTO driven strip till, SD 91 %, 5.66 t/ha, -404 €/ha	
A1	Winter wheat / Maize (non irrigated)	1980-2002	Chopping, PL, HA or RH, SD 74 %, 8.43 t/ha (reference), 354 €/ha	Chopping, Rotavator, DD 76 %, 8.49 t/ha (NS), 418 €/ha	Chopping, No till, DDSD 73 %, 8.48 t/ha (NS), 349 €/ha	
A1	Winter wheat / Maize (irrigated)	2007-2012	Chopping, PL, RH, SD 73 %, 8.58 t/ha (reference), 440 €/ha	Chopping, Rotavator, DD 63 %, 8.60 t/ha (NS), 484 €/ha STbis : Semavator 78 %, 8.24 t/ha (NS), 438 €/ha	No till, DDSD 59 %, 7.71 t/ha (**), 360 €/ha	No till, DDSD, Chopping after seeding 58 %, 8.34 t/ha (NS), 432 €/ha
A1	Maize (non irrigated) / Winter wheat	1979-1998	PL, RH, SD 88 %, 6.63 t/ha (reference), -414 €/ha	Stubble plough, RH, SD 88 %, 6.61 t/ ha (NS), -407 €/ha	PTO driven strip till, SD 88 %, 6.62 t/ha (NS), -320 €/ha	
A1	Maize (irrigated) / Winter wheat (+ CC)	2002-2017	CC, PL, RH, DDSD 92 %, 10.14 t/ha(reference), -327 €/ha	CC, RH or Vb, DDSD 93 %, 10.50 t/ha (**), -267 €/ha	CC, No till, DDSD 83%, 9.82 t/ha (NS), -332 €/ha	
A2	Sugar beets (irrigated) / Spring barley (+ CC)	2003-2015	SC, CC, PL, RH, Vb, DDSD 81 %, 101.9 t/ha, 704 €/ha	SC, CC, RH, DDSD 78 %, 98.3 t/ha, 602 €/ha	CC, No till, DDSD 58 %, 95.8 t/ha, 578 €/ha	
A2	Sugar beets (irrigated) / Spring barley (+ CC)	2012-2017	SC, CC, PL, RH, Vb, DDSD 81 %, 114.0 t/ha, 1015 €/ha	SC, CC, RH, DDSD 76 %, 111.2 t/ha, 911 €/ha		CC, Strip till*2, DDSD 81 %, 113.5 t/ha, 963 €/ha
A2	Winter wheat / Sugar beets	1999-2017	Vb, PL, RH, SD 67 %, 8.38 t/ha, 394 €/ha	Vb, RH, SD 65 %, 8.19 t/ha, 404 €/ha	Vb, DDSD 67 %, 8.45 t/ha, 422 €/ha	
A2	Spring peas / Winter wheat	1998-2003	SC, PL, RH, SD or DD 84 %, 5.41 t/ha, 373 €/ha	SC, RH, SD or DD 79 %, 5.15 t/ha, 338 €/ha STbis : SC, DDSD 80 %, 4.88 t/ha, 281 €/ha	No till, DDSD 75 %, 4.97 t/ha, 283 €/ha	Rotavator (Horsch SE) 86 %, 4.75 t/ha, 284 €/ha
A2	Winter faba beans / Winter wheat	2008-2012	SC, PL, RH, DDSD 101 %, 3.31 t/ha, 142 €/ha	SC, DDSD 95 %, 3.12 t/ha, 169 €/ha	No till, DDSD 84 %, 3.39 t/ha, 222 €/ha	
A2	Oilseed rape / Winter wheat	2014-2017	SC, PL, RH, DDSD 74 %, 3.83 t/ha, -83 €/ha	SC, SC, DDSD 72 %, 3.67 t/ha, -91 €/ha	No till, DDSD 54 %, 3.56 t/ha, -82 €/ha	Strip till, DDSD 82 %, 3.69 t/ha, -83 €/ha
A2	Spring barley / Pea or faba bean (+ CC)	1999-2014	SC, CC, PL, RH, SD or DD 75 %, 7.64 t/ha, 274 €/ha	SC, CC, RH, SD or DD 78 %, 7.61 t/ha, 289 €/ha STbis : SC, CC, DDSD 70 %, 7.56 t/ha, 275 €/ha	CC, No till, DDSD 69 %, 7.72 t/ha, 302 €/ha	
A2	Spring barley / Oilseed rape (+ CC)	2015-2017	CC, PL, RH or vb, DDSD 79 %, 7.44 t/ha, 231 €/ha	CC, SC, RH or Vb, DDSD 78 %, 7.65 t/ha, 280 €/ha	CC, No till, DDSD 47 %, 7.34 t/ha, 253 €/ha	

Rotation in C experiment from 2010 to 2016: Fallow (wheat destroyed in May)-Spring pea-Oilseed rape-Winter wheat-Spring barley-Maize-Winter wheat (% of emergence and yields have not been averaged)

CC: cover crop ; SC : Stubble cultivation with discs or tines ; PL : Plough ; RH : Rotary harrow ; HA: Harrow with reciprocating bars ; Vb: Danish tine cultivator ; HE: Spring tine harrow; SD: Shoe drill ; DD: Disc drill ; DDSD: Disc direct seeding drill

An economic assessment of soil tillage and crop rotation is presented on table 3 (net margin). There were very important differences between crops. Irrigation also had an impact. Soil tillage technique effect was far less important on net margin. As we included all crops and periods, the income from sales was lower on ST and NT by 61 €/ha than on CT, due to slightly lower yields on certain crops. The cost of mechanization was lower by 49 €/ha. It included a lower consumption of fuel of 27 l/ha. The net margin decreased by 5 €/ha on ST and NT as compared to CT. It was quite the same on average but we can see positive or negative differences depending on the crops and soil techniques on table 3. There was a trend to equivalent or improved net margin for ST and NT as compared to CT for maize, spring barley, winter faba bean and winter wheat. There was however sometimes exception for wheat (continuous wheat with straw non burnt, wheat after an irrigated maize in NT without any chopping of maize residues). Net margin was similar between soil tillage techniques for oilseed rape. Non-inversion tillage decreased the net margin of spring peas and sugar beets, including strip till for this last crop. We made two runs of strip tillage (15 cm in autumn, 5 cm in spring) and the savings on mechanization were not enough to compensate for the slight decrease in income from sales and the increase of inputs.
On average, ST and NT allow saving 1 h/ha as compared to CT. These savings depended on the crop, the preceding crop and the soil tillage technique. They were more significant for NT than ST. They ranged from half an hour to one hour and a half for NT.

<u>Impact of cover crops in the wheat–maize rotation</u>

Maize emergence was lower on average after cover crops were destroyed late winter (table 4). The seedbed moisture was sometimes more significant and it had an impact on seedbed quality (clods for ST, seed furrow closure for NT). Seeds were sometimes eaten by pests in NT (crows, slugs, rodents). These problems were usually not observed after cover crops were destroyed late autumn. In this case, seedbed parameters were quite the same with and without cover crops (residues, soil moisture). There was no impact of cover crops destroyed in autumn on maize yield for CT and ST. Cover crops increased NT maize yield. There was also no delayed effect of cover crops on winter wheat yield established after maize. Conversely, even if these effects were non-significant, we can see in table 4 that cover crops that were destroyed in late winter had a negative impact on maize (emergence and yield) and a positive impact on the following wheat (yield and protein content). The economic impact of cover crops is negative with a fall of net margin between 15 and 30 €/ha/year on the maize-wheat rotation. The cost of cover crop establishment is not compensated by agronomical benefits, even if there are benefits for the environment. Nitrogen maize fertilization was not adapted to the presence of cover crops.

Table 4: Difference of maize and wheat emergence, yields and net margin between cover crops and bare soils for the same soil tillage techniques according to soil tillage and cover crop destruction period. ANOVA results are in brackets (NS: p value > 0.10; .: p value <0.10; *: p value<0.05; **: p value<0.01; ***: p value<0.001).

	Autumn destruction			Winter destruction	
	CT	ST	NT	ST	NT
Maize emergence from 2002 to 2015 (plants/ha)	-974	-2 039	-877	-6 679	-3 802
Maize yield from 2002 to 2015 (t/ha at 15%)	-0.04 (NS)	0.01 (NS)	0.22 (.)	-0.27 (NS)	-0.26 (NS)
Wheat yield from 2003 to 2016 (t/ha at 15%)	-0.03 (NS)	0.15 (NS)	0.03 (NS)	0.17 (NS)	0.15 (NS)
Wheat proteins from 2003 to 2015 (%)	0.04	0.08	0.23	0.28	0.33
Net margin for maize from 2002 to 2015 (€/ha)	-42.0	-62.0	-71.0	-91.0	-94.0
Net margin for wheat from 2003 to 2016 (€/ha)	3.0	27.0	28.0	32.0	44.0
Net margin for the maize-wheat rotation (€/ha/year)	-19.5	-17.5	-21.5	-29.5	-25.0

Impact of the crop rotation on wheat yield

The long term experiment in Boigneville allowed comparing different crop rotation over a very long period. For almost 40 years, a wheat monoculture was in place, alongside to a wheat-maize rotation. Later, wheat was introduced in a longer rotation, after sugar beets.

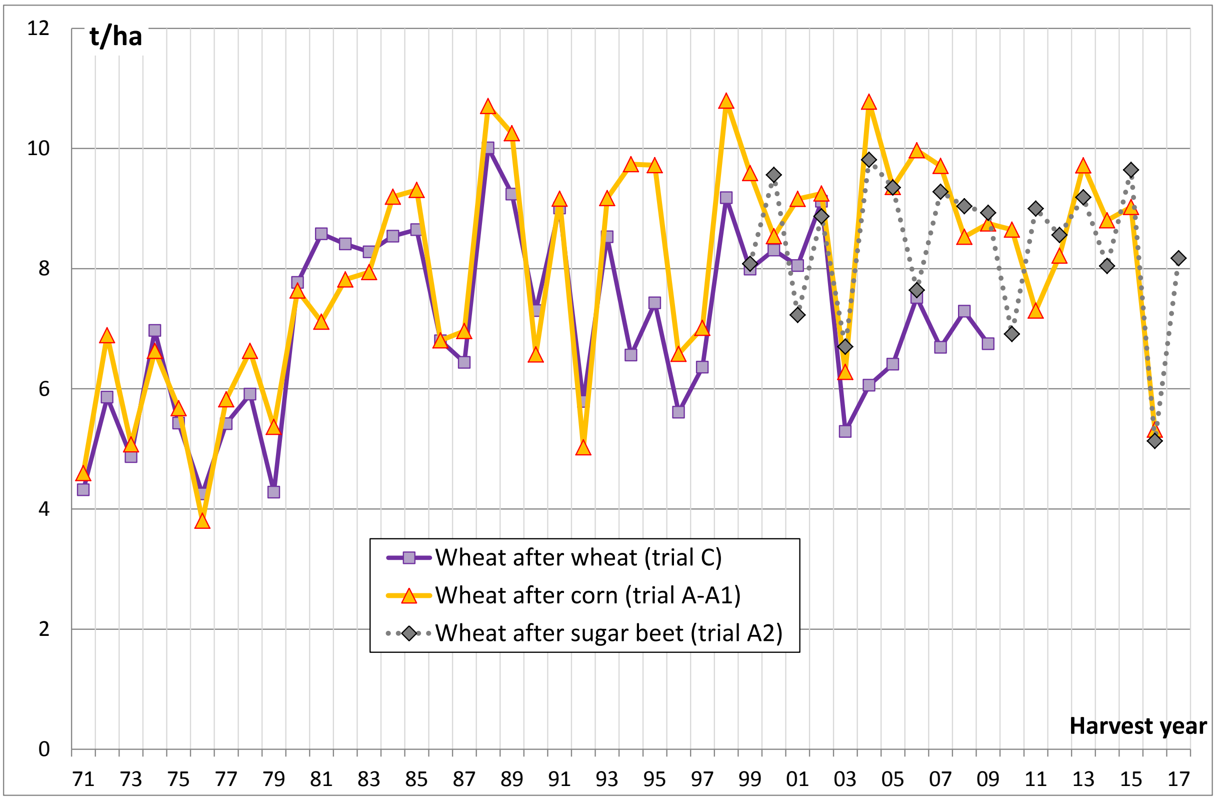
Surprisingly, from 1971 to 1990, the yield of wheat was the same on average in monoculture and after maize. This is quite unusual as compared to other long term experiments which showed a yield decrease for continuous wheat. Unfortunately, very few measurements of take all (*Gaeumannomyces graminis*) have been made in the 70's, maybe because this disease was not often present in the experiment.

After 1990, yield of wheat monoculture began to decrease as compared to wheat after maize. The gap became particularly big when the straw burning was stopped in the wheat monoculture. The causes are not well identified as it could be due to higher pest pressure (rye grass, yellow leaf spot *Dreschlera tritici-repentis*, nematodes…).

The impact of soil tillage techniques for the three preceding crops of wheat is described in table 3.

The experiments A and D allowed a comparison of maize yield after maize or wheat for 24 years. Continuous maize on ploughed plots yielded a little bit less (-4%) than maize after wheat on ploughed plots.

Figure 2: Comparison of winter wheat yield according to the preceding crop on ploughed plots. Wheat straw was burnt in experiment C from summer 1976 to 2000. The wheat monoculture on experiment C has been replaced by a crop rotation after 2010. Wheat after maize in 2017 has been replaced by spring barley because wild boars destroyed many wheat plots.



Impact of preceding crop and soil tillage on winter wheat diseases

Winter wheat diseases have been monitored in three experiments: C (wheat after wheat), A1 (wheat after maize) and A2 (wheat after sugar beets). Each year, wheat varieties were the same between the three preceding crops. Fungicide treatments were also the same. Results of our measurements are summarized in table 5. Take all (*Gaeumannomyces graminis*) has been observed only 3 years in the 70's. This low presence could explain the similar yield between wheat monoculture and wheat after maize for the first 20 years of the experiment. The 3 years when take all was measured in the experiment, it was not present on wheat after maize and more developed in wheat monoculture. In this crop rotation, take all attacked more wheat roots on CT than ST or NT. Dryland foot rot (*Fusarium spp.*, *Microdochium spp.*) has been measured on wheat in the 70's. Its presence of wheat stems was the same between wheat after maize or after wheat. This disease was more developed on ST or NT than on CT. Eyespot (*Oculimacula yallundae* and *O. acuformis*) has been measured in the field experiment in the 70's and from 2001 to 2009. The stem disease symptoms were more significant on continuous wheat as compared to wheat after maize or after beets. Whatever the preceding crop, eyespot was more developed on CT than on ST or NT.

During the 70's and early 80's, measurements did not show any impact of crop rotation (preceding wheat versus preceding maize) for three leaf diseases (brown and yellow rusts *Puccinia recondite* and *P. striiformis*, mildew *Blumeria graminis*). There was no impact of soil tillage on rust and little on mildew. Septoria was observed in the 70's (*Stagonospora nodorum*). There was no impact of soil tillage for wheat after maize. We had different results for *Septoria* from 2009 to 2014. The pathogen was then different (*Mycosphaerella graminicola*). For this later period, there were more *Septoria* symptoms on wheat after wheat than on wheat after maize or after sugar beets. For these three preceding crops, *Septoria* was more developed on ploughed plots than on ST or NT.

For 2 diseases, yellow leaf spot (*Dreschlera tritici-repentis* observed in 1974, 1975, 2003, 2005 and 2006) and Fusarium head blight (*Fusarium graminearum*, *Microdochium spp*. observed from 1999 to 2015), we observed a strong interaction between the preceding crop of wheat and soil cultivation. It is explained by the preceding crop residue management. As these residues are a source of inoculum for wheat, minimum tillage or no till favor the disease development on wheat. If the residues do not hold fungus inoculum, soil tillage doesn't have any impact. Yellow leaf spot was favored by wheat preceding crop straw. Fusarium head blight was favored by preceding maize residues. These diseases, for wheat after these preceding crops, are more developed in cases of non-ploughed plots and particularly in no till. After other preceding crops, the soil tillage doesn't have any impact. The measurements for Fusarium head blight were spikelet or grain infection and also mycotoxins (deoxynivalenol). For these 3 indicators, we observed after maize, a strong impact of soil tillage and of maize residue chopping. On the 2007-2012 period, the deoxynivalenol content expressed in percentage of CT were of 135% for ST (residues chopping, Rotavator), 234% for STbis (Rotavator), 193% for NTbis (direct drilling and then chopping) and 479% for NT (direct drilling).

For stem, leaf and ear diseases, even if we observed an impact of preceding crop of wheat or soil tillage, there was also a strong annual impact (in interaction with wheat variety and climate) and also of the fungicides as we compared with and without fungicides in the C experiment from 1974 to 2009. This comparison showed an average 1.2 t/ha gap of wheat yield, varying from 0 to 4.5 t/ha depending on the year. The gap was quite the same between soil tillage strategies: 1.09 t/ha for CT, 1.10 for ST and 1.24 for NT.

Table 5: Impact of preceding crop and soil tillage on wheat diseases. +++++: Disease strongly increased by soil tillage and/or the preceding crop; +++: Disease moderately increased by soil tillage or the preceding crop; +: Little presence of the disease; 0: Disease not present in this situation; ?: No data in this experiment. DON = Deoxynivalenol.

	Winter wheat Monoculture			Winter wheat After maize			Winter wheat After sugar beets		
	CT	ST	NT	CT	ST	NT	CT	ST	NT
Take all	+++	++	+	0	0	0	0	0	0
Dryland foot rot	+	++	++	+	++	++	?	?	?
Eyespot	+++++	+++	+++	+++	+	+	+++	+	?
Brown and yellow rusts	+	+	+	+	+	+	?	?	?
Mildew	+	+	++	+	+	++	?	?	?
Septoria	+++++	+++	+++	+++	+	+	+++	+	?
Yellow leaf spot	+++	++++	+++++	0	0	0	0	0	0
Fusarium head blight, DON	+	+	+	+++	++++	+++++	++	++	++

Common Smut (*Ustilago maydis*) on maize has been measured in the 70's. This disease was the more developed as the soil tillage was deeper (table 6). At the same period, there was no impact of ploughing on fusarium stalk rot (Fusarium spp.). Grain mycotoxins, caused by Fusarium on maize ears, have been measured every year from 2003 to 2011. There was a slight impact of soil tillage on deoxynivalenol, zearalenone, nivalenol and fumonisin. It was different according to the kind of mycotoxin and the year. We observed a stronger impact of no tillage on deoxynivalenol, zearalenone and nivalenol as there was a cover crop before maize. We can draw the hypothesis that Fusarium contamination was favored by oat residues left on the soil surface. The results still have to be confirmed under other conditions.

Table 6: Impact of cover crop and soil tillage on maize diseases. +++++: Disease strongly increased by soil tillage and/or the preceding crop; +++: Disease moderately increased by soil tillage or the preceding crop; +: Little presence of the disease; 0: Disease not present in this situation; ?: No data in this experiment.

	Maize, after winter wheat No cover crop			Maize, after winter wheat Oat cover crop, alone or associated with other species		
	CT	ST	NT	CT	ST	NT
Fusarium stalk rot	+	+	+	?	?	?
Common Smut	+++	++	+	?	?	?
Deoxynivalenol	+	+	++	+	++	+++
Zearalenone	+	+	++	+	++	+++
Nivalenol	+	+	+	+	++	++
Fumonisin	++	+	+	++	+	+

Impact of crop rotation and soil tillage on weeds

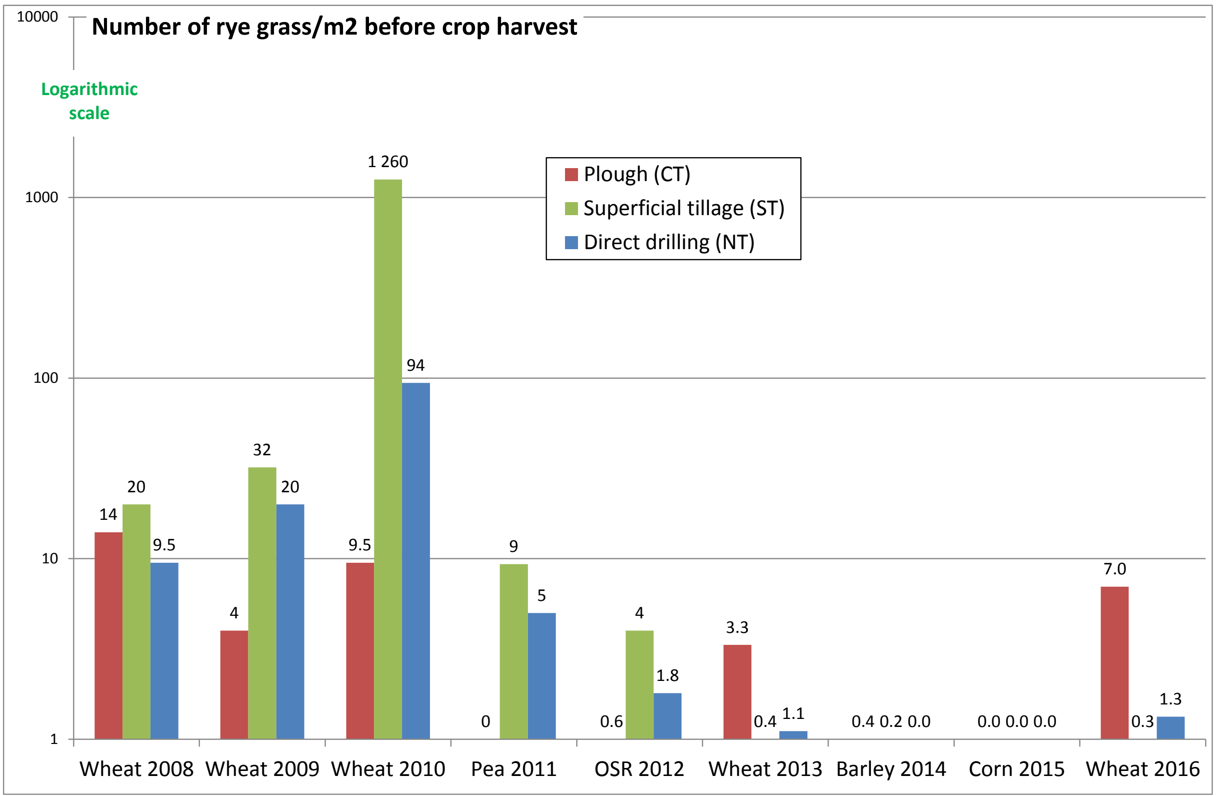
Most weed counts have been carried out ince 2008, at first in the C experiment, as rye-grass went out of control in the wheat monoculture. The measurements occurred in A1 and A2 experiments since 2012. The list of the main weeds observed is in table 7. We will later call them by their EPPO code.

Table 7: Main weeds species in A1, A2 and C experiments.

Common name	**Latin name**	**EPPO code**
Rye grass	Lolium sp.	LOLSS
Cockspur + Foxtail	Echinochloa crus-galli + Setaria verticillata	ECHCG + SETVE
Field bindweed	Convolvulus arvensis	CONAR
Groundsel	Senecio spp.	SENSS
Sow thistle	Sonchus sp.	SONSS
Dandelion	Taraxacum sp.	TARSS
	Polygonum spp., Fallopia spp., Persicaria spp.	POLSS
Cleaver	Galium aparine	GALAP
Goosefoot	Chenopodium spp.	CHESS
Black nightshade	Solanum nigrum	SOLNI
Pimpernel	Lysimachia sp.	ANGSS
Amaranth	Amaranthus spp.	AMASS

In the wheat monoculture in experiment C, a rye-grass population increased year after year because of its resistance to herbicides of HRAC groups A and B (figure 3). The population was the most important in ST: up to 1260 plant.m^{-2} in 2010, in spite of stale seedbeds in summer and early autumn. No till had a lower rye grass population than ST (94 plant.m^{-2}), probably because the seedbed was limited to the seed furrow and because the soil was still covered by straw after sowing. Ploughed plot population was the less significant (9.5 plant.m^{-2}). Considering the rye-grass population in ST and no till, winter wheat was destroyed chemically in May 2010 before rye-grass heading. There was no seed production in spite of a very important weed population. A crop rotation was then introduced. Thanks to the possibility of using herbicides with other modes of action than those used in wheat, rye-grass population became less and less significant, regardless of the soil tillage. It is noticeable that in wheat 2016, without spraying any herbicide against grasses this year, the population of rye-grass in NT and ST was under 1.5 plant.m^{-2}, but a significant population of rye-grass (7 plants.m^{-2}) was present on plots annually ploughed. It seems that burying rye-grass seeds helped to keep them alive longer than in case of superficial or no tillage, even if ploughing had a positive short term impact.

Figure 3: Number of rye-grass (LOLSS) in C experiment before crop harvest. It was the number of ears/m^2 in 2008, plant/m² since 2009. Wheat was destroyed in 2010 at heading (no ryegrass seed production). No herbicide against grasses was applied on 2016 wheat.



A synthesis of weed data according to soil tillage and crop rotation is shown on table 7. There was a strong effect of crop rotation on weeds, the flora being totally different between the experiments C, A1 and A2: spring and summer emergence flora dominates in experiment A1 where there is a high proportion of summer crop; in experiment C, there is mainly weeds emerging in autumn, and in A2 rotation, weed flora was more diversified, with more weeds able to emerge all around the year. Soil tillage effect on weed flora is deferent if we consider monocotyledonous or dicotyledonous species. In all rotation, when soil tillage decrease, grass population increase: ECHCG and SETVE in A1 experiment, LOLSS in experiment C before crop rotation introduction. After the wheat monoculture was replaced by a crop rotation, LOLSS populations decreased for all soil tillage techniques, but more slowly on ploughed plots. For the main dicotyledonous, the effect of crop rotation and tillage are very different. Cleaver (GALAP) showed a behavior close to rye-grass behavior, with the most important population in non-inverted plots in A1 or A2 experiments, except in experiment C when a crop rotation was introduced. The relatively short survival of rye-grass and cleaver seeds could explain these similar results. Perennials were also favored by NT, CONAR in maize-wheat rotation (A1) and TARSS in experiment A2 (beet-wheat-OSR-barley rotation). Different from cleaver, black nightshade (SOLNI) and pimpernel (ANGSS) were more numerous on CT in experiments A2 or C.

This data shows that weed management is complex, with many interactions between weed biology and the cropping system management including soil tillage, crop rotation, chemical or mechanical weeding…

Table 7: Main weed densities (plants/m^2) in A1, A2 and C experiments. WW = winter wheat, pea = spring pea, OSR = oilseed rape, SB = spring barley, Beet = sugar beets, WFB = winter faba bean.

		LOLSS	ECHCG + SETVE	CONAR	SENSS	SONSS	TARSS	POLSS	GALAP	CHESS	SOLNI	ANGSS	AMASS	Other species	**Total population**
Trial C	CT	7	non measured												
Continuous wheat and pea	ST	330	non measured												
2008 to 2011	NT	32	non measured												
Trial C	CT	2.09	0.00	0.33	0.00	0.44	0.16	0.09	1.49	0.16	0.33	0.64	0.04	0.43	**6.21**
OSR-WW-SB-Corn-WW	ST	1.00	0.00	0.00	0.00	0.20	0.07	0.00	0.42	0.24	0.11	0.04	0.07	0.48	**2.63**
2012 to 2016	NT	0.84	0.00	0.00	0.00	0.13	0.04	0.00	0.38	0.87	0.04	0.07	0.00	0.31	**2.69**
Trial A2	CT	0.00	0.00	0.00	0.39	3.66	0.06	0.15	0.00	0.12	1.55	0.00	0.25	0.61	**6.79**
Beet-WW-WFB or OSR-SB	ST	0.05	0.00	0.06	0.94	1.37	0.19	1.33	0.49	0.27	0.45	0.04	0.07	0.47	**5.73**
2012, 2014, 2015 and 2017	NT	0.04	0.00	0.00	6.56	1.54	0.81	0.33	1.06	0.62	0.39	0.00	0.70	1.33	**13.39**
Essai A1	CT	0.02	0.13	0.13	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	**0.68**
Corn-WW	ST	0.04	0.54	0.17	0.05	0.00	0.00	0.09	0.10	0.00	0.00	0.00	0.00	0.09	**1.11**
2012, 2014, 2015 and 2017	NT	0.00	6.27	1.06	0.06	0.13	0.04	0.19	0.78	0.00	0.13	0.00	0.00	0.65	**9.31**

<0.1 plantes/m^2	0.50< pl/m^2 <0.99	5.00< pl/m^2 <49.99
0.1< pl/m^2 <0.49	1.00< pl/m^2 <4.99	pl/m^2 >=50.00

<u>Soil bulk density and soil organic carbon monitoring</u>

The soil sampling methodology was designed to make unbiased estimates of soil organic carbon (SOC) stocks by fulfilling several requirements: i) measurement of stocks at the beginning of the experiment, ii) determining bulk density, iii) sampling below the maximum depth affected by soil tillage, iv) paying attention to the quality of C analysis, v) calculating stocks at equivalent soil mass and vi) measuring SOC over time, in order to make diachronic rather than synchronic studies.

Experiment A compared 3 tillage treatments, crossed with 6 crop managements. Variation in crop management included straw management (wheat straw and maize residues removed from 1982 to 1993 on STbis, NTbis and half of CT plots; wheat straw and maize residues returning to the soil in other plots or periods), crop rotation (A1 versus A2 experiments) and cover crop (absence or presence in A1 experiment). For the SOC calculation, we will consider only the tillage effects in this paper, averaging the crop management treatments, since no interaction was found between these two factors.

Arvalis and INRA sampled the soil at 12 dates between 1970 and 2017, on average every 4 years, from 0 to 33 cm, i.e. 5 cm deeper than the maximum ploughing depth. Results from the period 1970-2011 are detailed in Dimassi et al. (2014b). A new sampling campaign was carried out in 2017. Soil was sampled at 144 sites to a depth of 60 cm using a tubular gauge (6 cm diameter). Each soil core was divided into 7 layers (0-5, 5-10, 10-15, 15-28, 28-33, 33-40 and 40-60 cm) which were air dried, weighed and analyzed for C and N content. Bulk densities were measured in 72 sites using a gamma-densitometer (5-40 cm) and the cylinder method (other depths).

Calculations of SOC stocks during the 47 years of the experiment were made on equivalent soil mass basis (Ferchaud et al., 2015) using a dedicated R package (called SEME). The effect of treatments on SOC stocks was tested by analysis of variance (ANOVA) using a linear mixed effect model (nlme package).

Bulk density varied with time, soil tillage and depth (figure 4). In 2017, it was lower in the 0-5 cm layer in the reduced tillage treatments thanks to a higher organic matter concentration in this layer. Conversely, bulk density between 10 and 20 cm was higher in ST and NT (from 1.50 to 1.60) than in CT (between 1.40 and 1.50). These trends were also confirmed during the other years. In the layer which was ploughed long time ago and not tilled recently (25-30 cm), bulk density was greater in CT than ST or NT, but this trend was not detected earlier. Even if the bulk density was a little bit high in some cases, soil profiles showed many cracks especially when the soil dried in summer (shrinkage and swelling of clays). Earthworms could also influence soil structure, on NT particularly (figure 5). Their abundance was however rather small in our field experiment. Even if soil porosity was not very important in NT or ST between 10 and 20 cm, it did not seem to have a negative impact on crop yields (table 3) or water infiltration in winter. The analysis of soil structural porosity and its architecture is in progress and will be published later.

Figure 4: Soil bulk density at different depths for CT, ST and NT in A1 experiment in 2017. * p <0.05, ** p< 0.01, *** p<0.001.

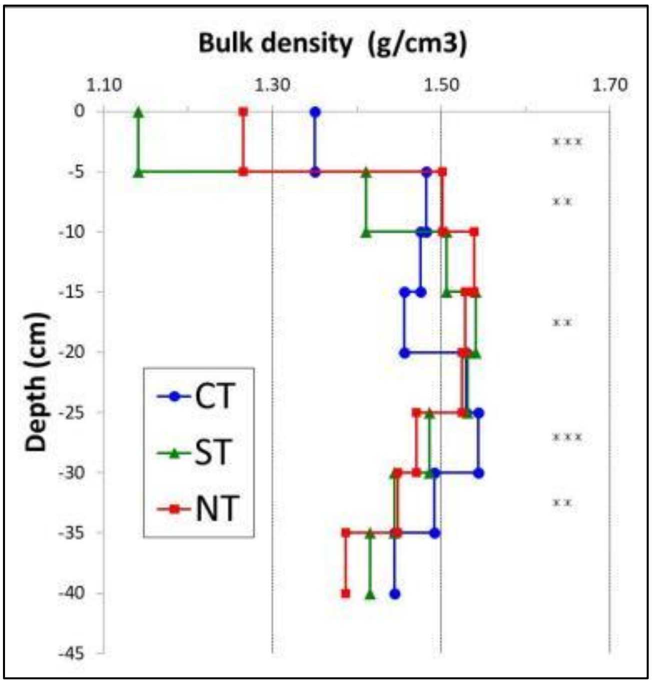
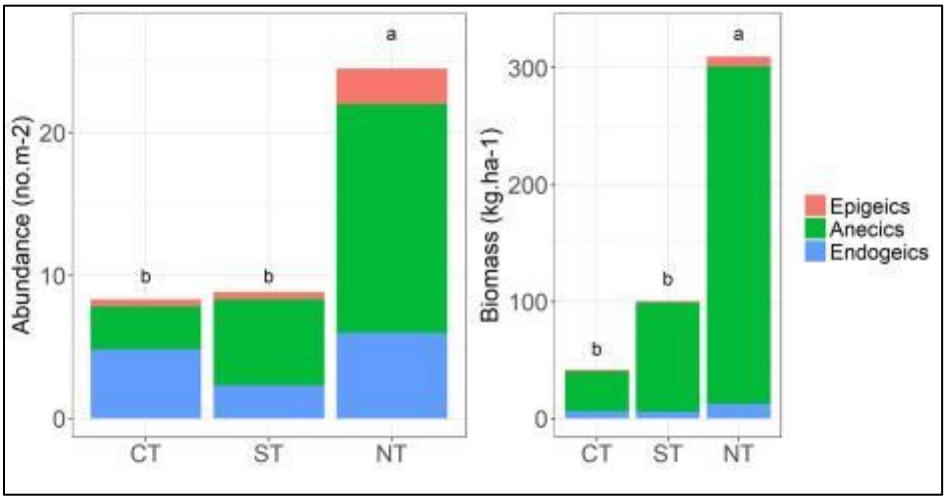


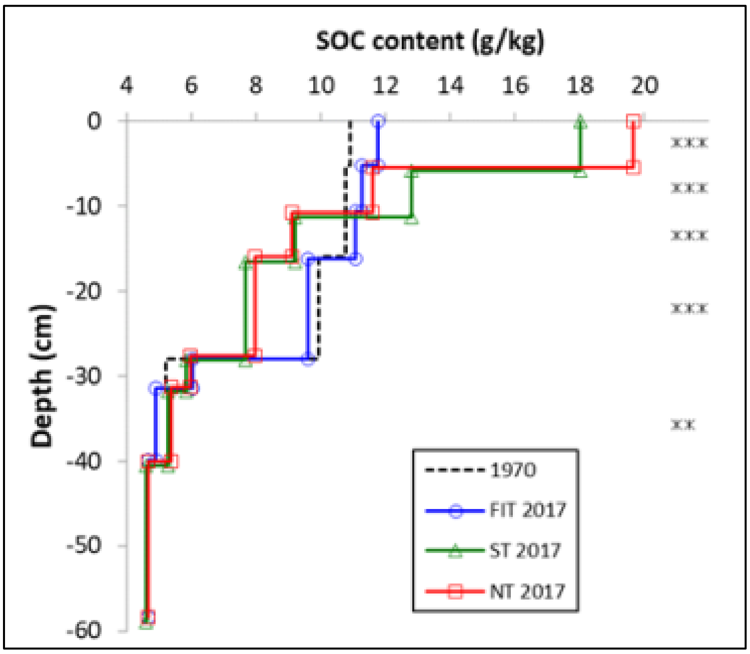
Figure 5: Earthworms abundance and biomass in A1 experiment in March 2018 in winter wheat (mustard extraction).



In 1970, the field exhibited a very small spatial variability: the mean SOC stock calculated between the three tillage treatments was 44.65 ± 0.31 t ha^{-1} in the reference layer (about 0-32 cm, corresponding to a soil mass of 4600 t/ha) and not significantly different. The initial SOC concentration was almost constant down to 28 cm (previous ploughing depth) and decreased rapidly below 28 cm (figure 6). In 2017, SOC concentration differed widely between tillage treatments: it markedly increased in the upper layer (0-10 cm) of NT and ST and also decreased significantly below 10 cm. This gradient concentration was also observed for total nitrogen, phosphorous, potassium and pH.

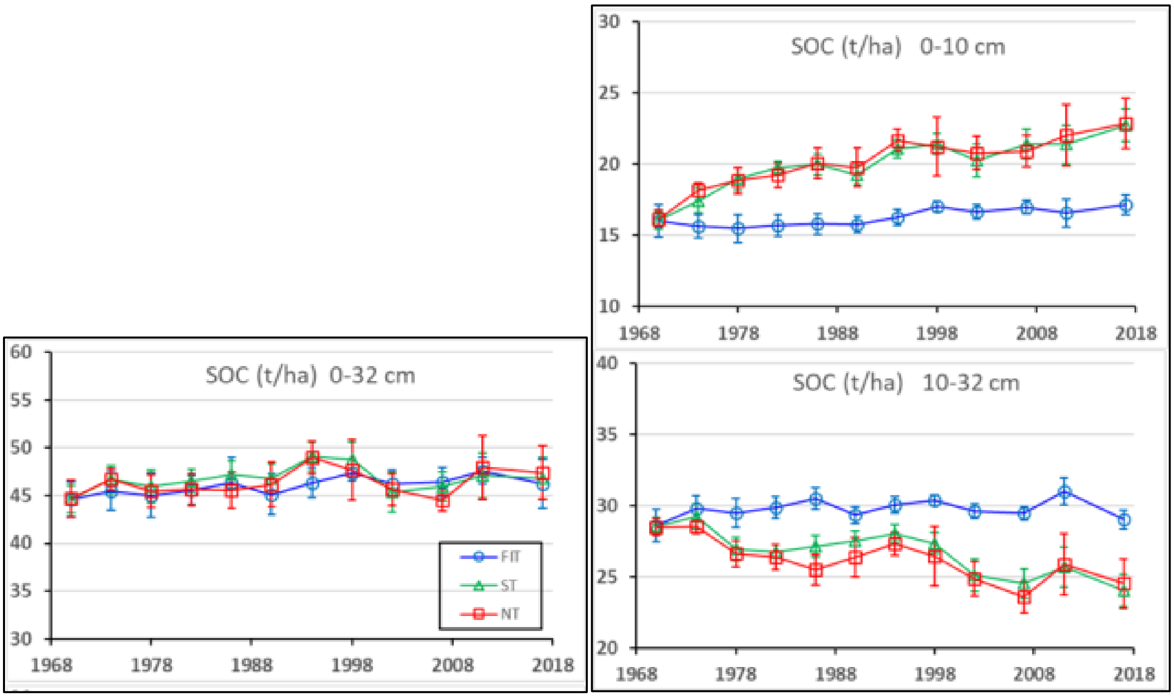
The SOC stratification was consistent with the depth of crop residue incorporation. Cumulative SOC stocks between 28 and 60 cm did not vary between treatments.

Figure 6: SOC concentration profile measured in 1970 and 2017. FIT = CT.



SOC stocks of ST and NT increased markedly with time in the upper layer (0-10 cm) but also decreased significantly in the layer 10-32 cm, whereas small variations were observed in the FIT treatment (figure 7). When summing up the two layers, SOC stocks in the reference layer followed a rather similar evolution between treatments, with a slight increase throughout time, and no significant difference between treatments at any time.
The poor effect of tillage on SOC storage cannot be attributed to differences in crop residues since the average crop yields did not differ between tillage treatments during the whole experiment. The decrease of SOC stock in the 10-32 cm layer shows that carbon mineralization is active in this layer in ST and NT treatments in spite of the absence of soil tillage.
In this long-term experiment, crop management (straw management, crop rotation and cover crop) had a stronger impact on SOC than soil tillage. Our results demonstrate clearly, in our pedo-climatic context, that soil carbon storage was not influenced at all by 47 years of reduced tillage, but was influenced by the amount of carbon inputs through crop residues. N_2O emissions have also been investigated in this experiment during several years and show no or little effect of tillage on greenhouse gas emissions (Oorts et al., 2007; Mary et al., 2014).

Figure 7: Evolution of SOC stocks during 47 years in three soil layers, according to soil tillage treatment. FIT = CT.



Conclusion and perspectives

The long-term soil tillage experiments carried out in Boigneville from 1970 contributed insightful information about the impact of soil tillage techniques on crops and soil. Soil tillage techniques were studied in different situations (straw management, crop rotation, autumn soil coverage). Our results showed how complex the interactions between soil tillage and the cropping system management are. Soil tillage impacts were, for example, different depending on the crop and the preceding crop for crop establishment, crop yield, wheat diseases, weeds… This experiment provided useful information for those wanting to adapt or improve their own cropping system, in conventional or conservation agriculture. We must however be careful with the extrapolation of results to other pedo-climatic situations or other kinds of cropping systems. The orthic luvisol on which the field experiment is developed is well adapted to most of soil tillage techniques, explaining that yield or economic results are quite equivalent between these techniques. Indeed, ploughing this soil is a very common practice thanks to the absence of stones, medium clay content and the absence of erosion as the soil surface is flat. Minimum tillage and no tillage are also well adapted to this soil type thanks to a good drainage and an average structural stability. Its ability to crack when it dries in summer helps create soil porosity after compaction without any deep soil tillage. In other types of soil or cropping systems, the impact of soil tillage can be totally different than what was observed in Boigneville (Soane et al., 2012; Stengel et al., 1984; Labreuche et al., 2014).
Data analysis is still in progress in 2018 or 2019 and will be published later, particularly on soil parameters such as SOC stocks, soil structure or potassium and phosphorous concentration.

In 2016, it was decided to set new objectives for this experiment. We consider that this experiment already answered many questions about soil tillage impact. On the other hand, there are many questions on weed management in the French context (social pressure, available herbicides, increasing weed populations resistant to herbicides…). The new objectives of the experiment are to develop and assess new cropping systems that control weeds with a greatly reduced use of herbicides (including glyphosate and active ingredients applied on crops). Of course, agronomical and mechanical levers will be put into practice such as crop rotation, soil tillage, mechanical weeding, sowing period… Our ambition is to develop these strategies for situations in which we accept ploughing the soil and in others without any deep soil tillage.
The "soil tillage" experiment has been stopped after harvest 2017 and a sampling campaign was then carried out in collaboration with INRA to characterize its final state on several aspects (soil density, SOC stocks, soil structure, soil biology…). This state will be the initial state of the new experiment starting in autumn 2018. A long crop rotation will be carried out: sugar beets - spring barley – hemp - winter wheat - winter oilseed rape - winter wheat. It will include only two crops present each year but with four replicates. Five strategies will be compared: reduced herbicides use with occasional ploughing (former CT plots); reduced

herbicides use with superficial tillage < 13 cm (former STbis plots); reduced herbicides use with superficial tillage < 5 cm (former NTbis plots); non restricted herbicides use with superficial tillage < 5 cm (former ST plots); non restricted herbicides use with no till or strip till for beets and oilseed rape (former NT plots). Measurements will focus annually on weeds, yield components and economic results. We will also keep investigating the impact of cropping system strategies on soil parameters, in order to check particularly mechanical weeding consequences on soil porosity and water infiltration.

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