Effect of cropping systems and climate on soil physical characteristics, field crop emergence and yield: A dataset from a 19-year field experiment

Jay Ram Lamichhane, Hubert Boizard, Carolyne Dürr, Guy Richard, Jean J. Boiffin

Data in Brief 39 (2021) 107581

Contents lists available at ScienceDirect

Data in Brief

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

Data Article

Effect of cropping systems and climate on soil physical characteristics, field crop emergence and yield: A dataset from a 19-year field experiment

Jay Ram Lamichhane[a,*], Hubert Boizard[b], Carolyne Dürr[b], Guy Richard[c], Jean Boiffin[b]

[a] AGIR, Université de Toulouse, INRAE, Castanet-Tolosan, France
[b] Agro-Impact, INRAE, Estrées-Mons, France
[c] DEPE, INRAE, Paris, France

ARTICLE INFO

Article history:
Received 27 July 2021
Revised 9 November 2021
Accepted 10 November 2021
Available online 16 November 2021

Keywords:
Morphological analysis
Ploughed layer mapping
"profil cultural" method
Seedbed
Soil tillage
Soil compaction
Soil porosity
Soil water content
Crop emergence
Crop yield

ABSTRACT

A long-term field experiment was conducted from 1989 to 2007 in northern France in a loamy soil to assess the cumulative effects of cropping systems (CSs) on soil compaction, soil porosity, soil structure, crop emergence and yield. Three CSs, including different crop rotations and cultivations (early or late sowing and harvesting), were compared. CS I was the succession of spring pea/winter wheat/oilseed rape (flax from 2001)/winter wheat while CSs II and III were the succession of sugar beet/winter wheat/maize/winter wheat. The latter two CSs consisted of different sowing dates, based on two distinct decision rules aimed at minimizing the risk of soil compaction in the CS II or maximizing the duration of the crop in the CS III. The tillage system was only mouldboard ploughing up to 2000 while a new treatment with superficial tillage (i.e. at 6 cm depth) was integrated since then into the experiment to compare the effects of annual ploughing and reduced tillage on changes in soil structure over time. Soil water content was measured for each field operation by taking samples every 0.05 m up to a depth of 0.30 m in the topsoil. Soil compaction and soil structure was evaluated after each sowing using a morphological approach and soil

* Corresponding author.
E-mail address: jay-ram.lamichhane@inrae.fr (J.R. Lamichhane).

https://doi.org/10.1016/j.dib.2021.107581

bulk density measurements. The "profil cultural" method was used to map soil structure variations in the topsoil below the seedbed. Dry bulk density was measured with a gamma-ray transmission probe. Seedling emergence rates and crop yield were also measured in relation to CSs. This dataset represents an important description of the changes in the soil compaction level, crop emergence rates and yield, in relation to CSs and climate, and the overall impact on seedbed structure variations for major field crops under northern France conditions. This information can be used as input variables of several soil-crop models aiming at evaluating the impact of CSs and climate on soil compaction and seedbed structures.

Specifications Table

Subject	Agricultural and biological sciences (general)
Specific subject area	Change in soil structure over time in relation to different cropping systems (crop rotation, sowing and harvesting dates, soil tillage)
Type of data	Table and photos
How data were acquired	Soil and crop measurements Morphological analysis of structure of the ploughed layer
Data format	Raw
Parameters for data collection	Soil moisture; soil porosity; Compaction in the topsoil; size of aggregates in the seed bed; seedling emergence rates; crop yield
Description of data collection	All the measurements were conducted under field conditions followed by laboratory analysis of the soil samples.
Data source location	Institution: INRAE City/Town/Region: Mons-en-Chaussée Country: France Latitude and longitude: 49°52′44″N 3°00′27″E
Data accessibility	Repository name: [Portail Data INRAE] Data identification number: [J2KCXM_2021] Direct URL to data: https://doi.org/10.15454/J2KCXM
Related research article	Boizard, H., Richard, G., Roger-Estrade, J., Dürr, C., and Boiffin, J. 2002. Cumulative effects of cropping systems on the structure of the tilled layer in northern France. Soil Tillage Res. 64:149–164. Boizard, H., Yoon, S. W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J. 2013. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil Tillage Res. 127:34–44. Dürr, C., Aubertot, J.-N., Richard, G., Dubrulle, P., Duval, Y., Boiffin, J. (2001). Simple: a model for simulation of plant emergence predicting the effects of soil tillage and sowing operations. Soil Science Society of America Journal, 65 (2), 414-422. Lamichhane, J.R., Boiffin, J., Boizard, H., Dürr, C., and Richard, G., 2021. Seedbed structure of major field crops as affected by cropping systems and climate: Results of a 15-year field trial. Soil Tillage Res; 206:104845. Available from: https://doi.org/10.1016/j.still.2020.104845 Richard, G., Boizard, H., Roger-Estrade, J., Boiffin, J., and Guérif, J. 1999. Field study of soil compaction due to traffic in northern France: pore space and morphological analysis of the compacted zones. Soil Tillage Res. 51:151–160. Roger-Estrade, J., Richard, G., Caneill, J., Boizard, H., Coquet, Y., Défossez, P., Manichon, H., 2004. Morphological characterisation of soil structure in tilled fields. From a diagnosis method to the modelling of structural changes over time. Soil Tillage Res. 79, 1:p 33-49

Value of the Data

- The soil compaction level and the consequent geometry of compacted zones differ from one cropping system to another. The database presented herein enables an assessment of the soil structure changes over time, taking into account soil compaction risk and natural or mechanical regeneration in conventional and reduced tillage systems. This knowledge is important to foster adoption of the CSs having lower impact on physical, chemical and biological soil properties. All this finally helps improve crop emergence, crop growth and productivity.
- The dataset presented can be used by researchers working at the crop-soil interface, including soil scientists and agronomists, using experimental and modeling approaches.
- The data can be used for modeling the changes in soil structure over time in interaction with CSs and climate, by comparing the soil compaction level presented here within other soil, climate and CSs contexts.

1. Data Description

The dataset includes three key variables (Table 1): (i) input variables (experimental variants) with different conditions of crop establishment (climatic conditions, cultural operations etc.), (ii) intermediate variables (collected in order to refine the analysis such as soil moisture), and (iii) output variables (soil porosity, soil compaction level, soil aggregate size, seedling emergence, and crop yield).

2. The Objective of the Experiment

The structure of the tilled layer of cultivated fields changes over time because of human actions (tillage, compaction due to field traffic) or natural actions due to weathering, root growth and fauna activity. The combined effects of these processes alter the spatial arrangement, size and shape of clods and aggregates and, consequently, the volume of the pore spaces inside and between these particles [1].

Northern France is an area of intensive agriculture that has an oceanic climate and loess soils. Crops are sown, managed and harvested using heavy machinery. This is especially true when the crop sequence includes maize (*Zea mays* L.) and sugar beet (*Beta vulgaris* L.) and when the farmer's objective is high yields. Sowing is performed as early as possible while harvesting is made as late as possible to maximize light interception. Under these conditions, the risk of soil compaction is one of the key concerns in this area.

The long-term effects of CSs on soil structure were poorly known in 1990 and no information was available on the risk of irreversible compaction and its consequences for root distribution,

Table 1
Key variables measured and their units.

Main variable	Sub variable	Unit
Soil moisture	Water content	$g\ g^{-1}$
Soil compaction Index	Shear strength	$m^2\ m^{-2}$
Porosity	Bulk density	$Mg\ m^{-3}$
	Structural void ratio	$m^3\ m^{-3}$
	Structural porosity	$m^3\ m^{-3}$
The degree of compaction	The proportion of Δ, Φ and P structures	$m^2\ m^{-2}$
Aggregate	Size	mm
	Content/size in the seedbed	$g\ g^{-1}$
Crop growth	Seedling emergence	%
Crop performance	Yield	$t\ ha^{-1}$

nutrient uptake, seedbed condition, and crop establishment. Difficulties to evaluate the dynamics of changes in soil structure over time and, more specifically, to understand the specific effects of anthropic and natural factors on the change of the soil structure over time were the key reasons behind this knowledge gap. Indeed, experiments in research stations are often conducted without being able to take into account the soil moisture conditions at the time of tillage. In addition, it is necessary to take into account the spatial variations of the soil structure caused by tillage, wheeling and weather conditions to precisely understand the long-term effects of CSs on soil structure.

To answer the above-mentioned issues and to fill the knowledge gap, a long-term experiment was set up in 1989 as described below.

3. Study Site, Climate and Soil Data

The study site was located in northern France, at Estrées-Mons (50°N latitude, 3°E longitude, 85 m elevation). Data collected in these field experiments depend on climatic factors. Consequently, the effects of CS on all the corresponding variables result from interactions with climate. Soil structure evolution is strongly affected by drying-wetting and freezing-thawing episodes, which depend on rainfall and temperature during the intervals between tillage operations. Another indirect but very important influence of climate occurs though the effect of soil moisture on soil mechanical properties at the time of tillage operations. Crop emergence rates, early growth and yields also depend on climate, in various, and, more or less complex, ways. Meteorological data were collected at the experimental site or close to the site, at Fontaine les Clers (20 km South-East; for detailed information: agroclim-contact@inrae.fr).

The soil is a Haplic Luvisol (FAO classification). The 0–30 cm horizon has a silt loam texture (19% clay, 76% silt, 5% sand and 1.7% organic carbon on average; Table 2) and a pH of 7.6. The gravimetric soil water contents measured at −10, −32, −50, −100 and −1500 kPa were 0.253, 0.229, 0.208, 0.175 and 0.084 g g^{-1} respectively. The average atmospheric temperature was 11.1 °C while the average annual rainfall was 713 mm.

Table 2
Description of the experimental treatments with crops and soil clay content for the first four years.

CS	Year 0	Year 1	Year 2	Year 3	Block 1 Plot	Block 1 Clay (%)	Block 2 Plot	Block 2 Clay (%)	Average clay (% ± SD)
I	OR	WW	SP	WW	5	19.7	20	18.4	19 ± 1
	SP	WW	OR	WW	6	17.3	19	20.9	19 ± 2
	WW	SP	WW	OR	7	20.1	18	19.6	20 ± 0
	WW	OR	WW	SP	8	19.9	17	21.3	21 ± 1
II	M	WW	SB	WW	2	21.6	23	17.1	19 ± 2
	SB	WW	M	WW	3	20.2	22	16.6	18 ± 2
	WW	M	WW	SB	10	15.7	14	20.7	18 ± 3
	WW	SB	WW	M	11	18.6	15	17.8	18 ± 0
III	M	WW	SB	WW	1	21.3	24	17.6	19 ± 2
	SB	WW	M	WW	4	20.9	21	18.2	20 ± 1
	WW	M	WW	SB	9	17.9	13	19.2	19 ± 1
	WW	SB	WW	M	12	18.8	16	17.2	18 ± 1

CS: cropping system; SP: spring pea; WW: winter wheat; OR: oilseed rape, SB: sugar beet; M: maize.

4. Experimental Treatments

4.1. Cropping systems

Three CSs were established to obtain a wide range of soil compaction intensity while respecting agricultural features of the region. These factors included possible crops and rotations, and time schedule for field operations.

CSs I: rotation in the CS I was spring pea (SP; *Pisum sativum L.*)/winter wheat (WW; *Triticum aestivum L.*)/winter oilseed rape (OR; *Brassica napus L.*), which was replaced by flax from 2001 (F: *Linum usitatissimum*)/ WW. Sowing and harvesting were carried out either in summer or early autumn, *i.e.* during the dry period of the year, except for pea that was sown in early spring. The risk of compaction in this CS is low compared with the other CSs described below.

CSs II and III: Rotation in these CSs was sugar beet (SB; *Beta vulgaris L.*)/WW/maize (M; *Zea mays L.*) /WW. CS II was managed so as to avoid sowing and harvesting in wet conditions while CS III was managed so as to maximize SB and M production. SB and M were sown in early spring, and harvested in late autumn, that maximized soil compaction risks.

Only mouldboard tillage systems were chosen in 1989, which were the most common in northern France. From 2000, because different types of tillage (reduced, minimum and no tillage) were developing in many parts of the world, there was an increasing interest in these systems in the region, even though their implementation was unlikely feasible in CSs characterized by high compaction risks . Consequently, a new treatment with superficial tillage (*i.e.* at 6 cm depth) was added into the experiment in order to compare the effects of conventional and reduced tillage on the soil structure evolution.

4.2. Experimental design

From 1989 to 2000, the experimental design consisted of two blocks (Table 2). The crops belonging to each CS were planted every year that led to 24 plots in total . This design allowed comparing CSs including key common crops every year to maximize the number of CS-crop-year combinations, which can be used in any future study. In such a way, a given CS-crop combination comes back on the same experimental plot at a 4-year time interval, which means that results obtained on a plot in a given year are strictly comparable only to results distant 4 (or multiples of 4) years before or after. The mean plot size was 0.40 ha that allowed traffic patterns of machinery similar to those found on commercial farms.

The experimental plots were not selected at random and were grouped by crop species to facilitate the implementation of the cropping practices (Fig. 1). A special attention was paid to ensure that the soil textures were well distributed between the experimental treatments. The average variation in texture between treatments was between 18 and 21% (Fig. 1). From 2000, block 1 and block 2 were managed under conventional and reduced tillage system, respectively.

4.3. Decision making rules

Rules for decision making in each CS were chosen to take into account the soil moisture conditions at the time of tillage. Because the sequence of cropping practices in commercial farms depends on multiple factors (competition between crops, availability of the farmer etc.), the decision rules were based on agronomic criteria enabling to reproduce sequences of practices corresponding to different possible strategies of farmers. In system CS I, the physiology of the chosen crops leads *a priori* to a low-risk compaction (Table 3). In CS II and III, sowing and harvesting could be done in early spring or late autumn when soil moisture was often high. Consequently, the risk of compaction is high *a priori*, especially in autumn with heavy harvesters. Therefore,

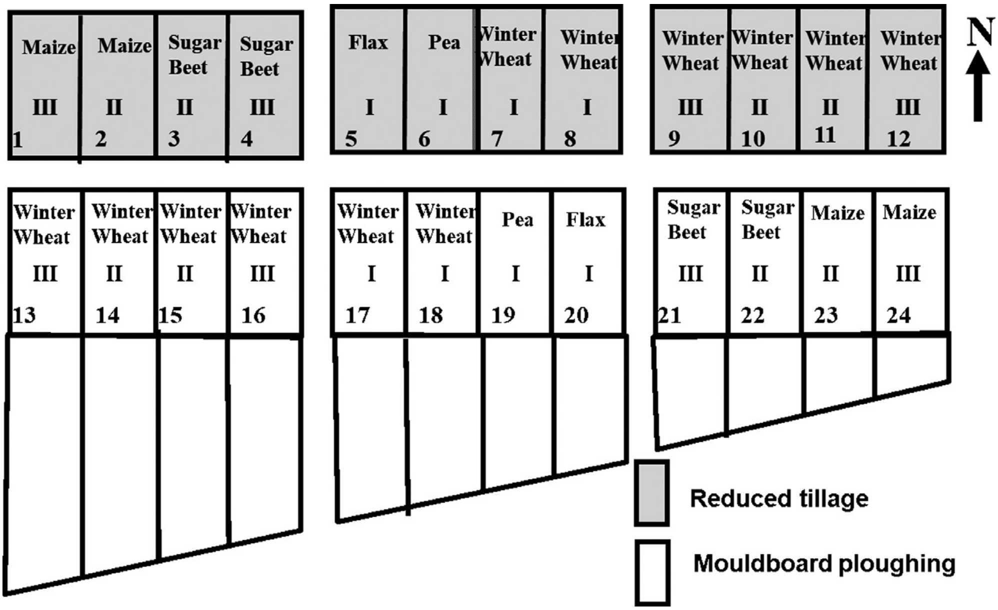

Fig. 1. The experimental layout of the field trial in 2002 with the location of the different crops for each cropping system. The number reported at the bottom of each plot indicates the names of the experimental plots.

Table 3
Rules for decision making from 1990 to 2000 (from Boizard et al. [2]).

			Rules for decision making	
Operation	Crop	Cropping system	Possible date from	Agronomic rule
Sowing	Spring pea	I	1 February	w* ≤ 0.25 in the 0-10 cm layer
Sowing	Sugar beet	III II	1 March 20 March	$w \leq 0.25$ in the 0-10 cm layer $w \leq 0.20$ in the 0-10 cm layer and ≤ 0.22 in the 10-20 cm layer
Sowing	Maize	III II	1 April 20 April	$w \leq 0.25$ in the 0-10 cm layer $w \leq 0.20$ in the 0-10 cm layer and ≤ 0.22 in the 10-20 cm layer
Sowing	Oilseed rape	I	25 August	$w \geq 0.08$ in the 0-30 cm layer
Sowing	Winter wheat	I II III	10 October 10 October 10 October	$w \geq 0.08$ in the 0-30 cm layer and $w \leq 0.27$ in the 0-30 cm layer whatever the system
Harvesting	Spring pea Oilseed rape Winter wheat	I II I,II, III	-	At crop maturity and $w \leq 0.27$ in the 0-30 cm layer whatever the crop or system
Harvesting	Maize	II III	-	At crop maturity of the early cultivar and $w \leq 0.27$ in the 0-30 cm layer At crop maturity of the semi early cultivar and $w \leq 0.27$ in the 0-30 cm layer
Harvesting	Sugar beet	II III	20 September 10 November	At the first harvesting date on the farm and $w \leq 0.27$ in the 0-30 cm At the last harvesting date on the farm and $w \leq 0.27$ in the 0-30 cm

* w: soil water content at the time of field operation (g g^{-1}).

Table 4
Rules for decision making from 2000 to 2008 (from Boizard et al. [3]).

			Rules for making decision	
Operation	Crop	System	Possible date from	Agronomic rule
Sowing	Spring pea	I	1 February	$w^{*} \leq 0.23$ in the 0-20 cm layer
Sowing	Sugar beet	III	1 March	$w \leq 0.25$ in the 0-5 cm layer
		II	1 March	$w \leq 0.23$ in the 0-20 cm layer
Sowing	Maize	III	1 April	$w \leq 0.25$ in the 0-5 cm layer
		II	1 April	$w \leq 0.23$ in the 0-20 cm layer
Sowing	Flax	I	1 March	$w \leq 0.23$ in the 0-20 cm layer
Sowing	Winter wheat	I	10 October	$w \leq 0.23$ in the 0-20 cm layer
		II	10 October	to 15 October and $w \leq 0.25$ after
		III	05 November	$w \leq 0.25$ in the 0-5 cm layer
Harvesting	Spring pea	I		At crop maturity and $w \leq 0.27$
	Oilseed rape	II	-	in the 0-20 cm layer whatever
	Winter wheat	I,II, III		the crop or system
Harvesting	Maize	II		Grain moisture < 38% and $w \leq 0.27$ in the 0-20 cm layer
		III	-	
			Before November 5th	Grain moisture < 30% and $w \leq 0.27$ in the 0-20 cm layer
			After November 5th	Grain moisture < 38% and $w \leq 0.27$ in the 0-20 cm layer
Harvesting	Sugar beet	II	20 September	At the first harvesting date on the farm and $w \leq 0.27$ in the 0-20 cm
		III	10 November	$w \leq 0.27$ in the 0-20 cm layer
Disc harrow			1 September	$w \leq 0.23$ in the 0-20 cm layer
Ploughing			1 November	$w \leq 0.24$ in the 0-20 cm layer

* *w:* soil water content at the time of field operation (g g^{-1}).

the decision rules have been established to take into account different management strategies of farmers: e.g., limit compaction in CS II and maximise production in CS III (Table 3).

From 2000, the rules for decision making were modified to take into account the experience gained (*e.g.* M maturity date occurred earlier in the 1990-2000 decade due to climatic change) and the necessary adaptation with the implementation of reduced tillage (*e.g.* soil water content at drying was different between reduced and plough tillage systems) (Table 4).

4.4. Description of cultural operations

In the conventional tillage system, each plot underwent a 30 cm depth mouldboard ploughing every year. This was done before the sowing of spring crops between November and January to take advantage of the effect of climatic conditions (freezing/thawing and wetting/drying) on the soil surface horizon. Mouldboard ploughing for WW and OR was carried out just before sowing. Major field operations performed after the harvest of a preceding crop and before secondary tillage were: chopping (only for M) and stubble disking (only for SP and OR). Seedbed preparation was performed with a combination harrow (with several rows of small tines and two rows of rollers) for SB, M and OR at 6-8 cm depth. WW and SP were sown using a combined rotary harrow and drill performing tillage and sowing was performed in one pass. Independent of the crop, seedbed preparation was followed by sowing within a maximum of 24 hours for all crops and the depth of the seedbed layer ranged from 3 to 9 cm (average 5.5 cm). The drill for WW and SP was 3 m wide with a 17 cm row spacing. A 12-row drill with a 45 cm row spacing for SB and a 6-row drill with a 80 cm row spacing for M were used. The equipment used for seedbed preparation had similar characteristics in terms of weight (6.5–8 Mg), tyre width (0.70 m), working widths (3 m), and inflation pressure (70 kPa). In contrast, the harvesting equipment was much heavier (about 15 Mg) with a high inflation pressure (200-300 kPa), and a wide variation occurred in the percentage of the experimental plot covered by wheel tracks (29–77%).

In autumn 1999, a new treatment with superficial tillage (*i.e.* at 6 cm depth) was integrated into the experiment in order to compare the effects of conventional and reduced tillage on the soil structure evolution. Every first and second block was managed under conventional and reduced tillage, respectively. The main difference between these two systems was that a compact disc cultivator at 6 cm average depth (ranging from 4 to 8 cm) replaced mouldboard ploughing. From 2000, the drill with only coulters was replaced by a disc drill on the whole experiment to ensure better management of harvest residues under reduced tillage [3].

The main characteristics of the machinery used are shown in Table 5. The equipment used for the cropping operations differed in terms of machinery weight (4.5–16.5 Mg), tyre width (0.30–0.70 m) and inflation pressure (70–300 kPa), leading to a wide range of ground pressures, as evaluated with the model proposed by O'Sullivan et al. [4]. Working widths were also different from one operation to the others (2.7–5.4 m), leading to a wide variation in the percentage of the experimental plot covered by wheel tracks (11–44%).

A full description of the field operations from 1989 to 2007 are presented in the attached dataset. The soil water profile of the topsoil up to 0.3 m depth was determined gravimetrically before each field operation (four replicates per plot), at every 0.05 m depth (see "1_ cultural operations"). The tillage direction was always the same lengthwise. The location of the wheel tracks was recorded after each field operation on a transect over the plot width (see "8_wheel track mapping"). The working depth was measured by digging a pit perpendicular to the tillage direction after each tillage operation: thickness of the seedbed (H1) and the topsoil below seedbed (H5) are reported in "5_morphological approach".

5. Soil Structure Measurements and Indicators

5.1. Bulk density

Bulk density measurements were performed from 1989 to 2007 (see datasheet "4_porosity"). From 1989 to 1997, dry bulk density was measured after each operation in the middle of the tracked zones toward the direction of the wheel track and in the untracked zone. The objective of the measurements was to evaluate soil compaction due to wheeling. A γ–ray transmission probe was used (three or four replicates per plot) at 0.05, 0.10, 0.15 and 0.20 m depth from the soil surface (probe with two tubes placed 0.30 m apart). From 2000 to 2007, the focus of bulk density measurements was shifted towards a better assessment of cumulative effects of the CSs. Therefore, dry bulk density was measured following each sowing in the unwheeled zones using a gamma ray transmission probe (10 replicates per plot) at a depth of 0.125 m, 0.175 m and 0.225 m from the soil surface (probe with two tubes placed 0.30 m apart).

In Richard et al. [6], the structural porosity (ns) was calculated from dry bulk density measurements in the field using the following formula:

$$ns = 1 - \frac{\rho a}{\rho t(w)}$$

where ρ_a is the soil bulk density (Mg m^{-3}), ρ_t(w) the textural soil density (Mg m^{-3}) at a water content w at the time of bulk density measurement. The textural soil density was measured as a function of soil water content using small aggregates (2 ± 3 mm diameter) as described by Monnier *et al.* [5]. Small aggregates were chosen to avoid the presence of cracks caused by tillage and weathering, and to describe pore space due to the particle arrangements alone. The aggregates were first re-wetted on a porous plate in a partial vacuum of ca. 70 kPa in a pressure cell and submitted to 0.3 kPa water suction for two days. The initially saturated aggregates were gradually dried to zero water content under silica gel. A sample (2 ± 3 g) was taken for each loss of 0.01 g g^{-1} water content. The volume of the aggregates at each water content was measured in kerosene using Archimedes' principle. The aggregates were then oven-dried to measure the

Table 5
Main characteristics of the equipment used during the study.

Operation	Crops	Tractor type	Tool Characteristics (working width (m))	Total Weight (Mg) (tractor and tool)	Maximum tyre width (m)	Maximum tyre inflation pressure (kPa)	Mean soil pressure (kPa)[a]	Compaction Group	Observed working width (cm)	Soil area covered by wheel tracks (%)
Chopping	M	Case IH 1056	Chopping machine	8.2	0.45	200	65-80	2	4.0	22
Stubble discing	SP and OR	Case IH 956	Disc	7.5	0.65	70	50-60	1	3.4	38
Mouldboard ploughing	All	Case IH 1056	4-bottom mouldboard plough (16 inches)	6.5	0.45	200	-	-		
Primary tillage from 2000 in reduced tillage	All	Case IH 956	compact disc cultivator	7.5	0.65	70	-	-	3	44
Seed-bed preparation	SB, M and OR	Case IH 956	Combination harrow	6.5	0.65	70	50-60	1	2.95	44
Combined seed-bed preparation and sowing	WW and SP	Case IH 956	Rotary harrow and seeder	8	0.65	70	50-60	1	2.95	44
Sowing	OR	Renault 851.4	12 row seeder	5.5	0.30	220	80-90	2	5.4	11
Sowing	SB	MF 575	12 row seeder	5	0.30	220	80-90	2	5.4	11
Sowing	M	Fiat 780	6 row seeder	4.5	0.40	220	70-90	2	4.8	17
Harvesting	WW, SP, OR,	_	MB8060, MBTX34	15	0.70	200-250	80-100	3	4.9	29
	M		Axial FL 1460				90-110	3	4.0	35
Harvesting	SB	_	Matrot (6 row harvester)	15	0.60	200-250	90-100	3	2.7	44[c]
Transport[d]	SB	Case IH 1056 and Case IH1055	8-Ton trailer	16.5[b]	0.45	300	100-110	3	2.7	33[c]

[a] Calculated from O'Sullivan et al. [4] as a function of axle load, type width, diameter and inflation pressure.
[b] When fully loaded;
[c] Mean surface affected by wheel tracks at sugar beet harvesting was estimated 65% including harvesting and transport;
[d] Traffic of trailers on experimental field only occurs during sugar beet harvesting; SP: spring pea; WW: winter wheat; OR: oilseed rape, SB: sugar beet; M: maize.

volume of water and the mass of the aggregates. The bulk density of the aggregates, called as the textural bulk density, was calculated from the soil water content.

In Richard et al. [6], measurements for 55, 30 and 90 plots after seedbed preparation, sowing (only SB and M) and harvesting, respectively, were annually compared. We assumed that there was 0.05 m of fine soil in the wheel track ruts after seedbed preparation. Therefore, we compared the effect of the different management interventions on soil compaction by analysing the structural porosity at 0.05 and 0.15 m below the rut surface in case of sowing and harvesting, and at 0.10 and 0.20 m below the seedbed surface in case of seedbed preparation. The structural porosity values at 0.05 and 0.15 m below the rut were correlated with the water content of the soil depth ranges (*i.e.* 0.05 ± 0.15 m and 0.15 ± 0.25 m) measured before wheeling to compensate for soil movement during compaction.

In Boizard et al. [3], the indicator used to assess cumulative effects of the CSs was the structural void ratio (eS). This indicator was calculated from field bulk density ρa and textural soil density ρt, both measured at the same water content, as:

$eS = \rho s/\rho_a - \rho_s/\rho_{t,}$ with ρ_s being the particle density.

5.2. Morphological approach

In parallel to the analysis of the porosity, a morphological description of the topsoil below the seedbed was carried out every year, after each sowing date, from a randomly located 3 m wide soil profile perpendicular to the tillage and wheeling directions (see datasheet "5_morphological approach"). We used the "profil cultural" method proposed by Manichon [7] and presented in detail in Boizard et al. [2] to map soil structure variations in this tilled layer. The different types of structural porosity were identified by exerting lateral pressure with a knife. The highly compacted zones containing specific features (no visible macropores, a massive structure and a smooth breaking surface) were delimited in slight relief on the observation face. Four structure types were identified. The Δ structure is characterised by a massive structure and no visible structural porosity. The Δ structure is related to severe compaction events. Δ zones of soil are found under wheel tracks when traffic in wet conditions has severely compacted the soil, destroying the structural porosity. Δ clods were produced when these zones were fragmented by ploughing or shallow tillage. Weathering can alter the Δ structure: due to wetting–drying or freezing–thawing cycles, cracks gradually appear in Δ clods and zones. When such cracks are observed, the structure is classified as Φ . From 2000, since a specific platy soil structure was often observed at the bottom of the seed bed in reduced tillage, we distinguished this platy soil structure which we called P from the remaining Φ structure. In contrast to the Δ structure, soil zones showing visible aggregates with a high level of intra- and interaggregate porosity (whose origin is not weathering) are classified as Γ.

From 1989 to 2000, stereoscopic photographs were taken 1 m from the soil profile at intervals of 0.065 m. The Δ zones were drawn manually in the laboratory from photographs with a stereoscope and were digitalized for image analysis. The soil profile was divided into three regions identified by the presence and origin of the tractor wheel tracks occurred after the last ploughing. The three regions identified were those with: (i) wheel tracks made at seedbed preparation (rut not visible); (ii) wheel tracks made at crop sowing or at crop harvesting (visible rut); and (iii) no wheel tracks from last ploughing. The area of individual Δ zone of the ploughed layer immediately beneath each kind of track was calculated. From 2000, digital photographs were taken 1 m from the soil profile at intervals of 0.40 m. Image analysis was performed using Optimas 6.5 software (Media Cybernetics, 1999). A thresholding procedure followed by hand drawing the contour enabled a clear separation of the types of structural porosity, so as to localize Δ, Φ, P and Γ zones and quantify their areas and Feret diameters.

In Richard et al. [6], the main objective of the paper was to examine the changes in soil compaction due to traffic under a wide range of soil conditions, describing the intensity and the soil volumes affected. The effects of wheeling on soil compaction were expressed as the percentage of the area of the ploughed layer immediately beneath the wheel track that had massive Δ zones in contact with the bottom of the seedbed. This indicator in our dataset has been named as "I_Compact by wheeling" in the datasheet "5-morphological approach". Measurements were performed over seven experimental years (*i.e.* from 1990 to 1996). In each soil profile, we determined the origin of the cultural operation (seedbed preparation, sowing, harvesting), with a mean soil water profile before the management intervention, a mean structural porosity at the depths of 0.05, 0.10, 0.15 and 0.20 m in the wheeled and unwheeled zones, and a percentage of areas of these zones.

In Boizard et al. [2], the objective was to evaluate the cumulative effects of CSs on the structure of the tilled layer. The proportion of soil in the ploughed layer having a Δ structure was calculated in the area of the ploughed layer under the seedbed outside the part of the field rolled by any wheel since ploughing, *i.e.* exempt from any compaction since ploughing, in order to analyze the cumulative effects of CS on soil structure. This indicator included Δ zones and Φ zones (Φ are Δ zones in which cracks have appeared due to weathering). The criterion in this dataset has been called as "I_Compact H5" in the table "5-morphological approach", and was calculated for the whole soil profile, but also in the wheeled and the unwheeled zones. The differences in these variables were investigated by analyzing nine profiles in a plot in 1994. The mean, the standard deviation and the coefficient of variation were 28%, 6% and 22%, respectively. The latter value was used as an estimate of the precision of the measurement of the percentage of Δ, P and Φ areas.

In 2000, Roger Estrade et al. [8] applied the indicator "I_Compact by wheeling" to modelling change in soil structure over time using the SISOL model. The relationship between the soil water content at the time of cultivation and creation of Δ areas allowed to estimate creation and loss of Δ zones. Soil compaction during each field operation was determined by the proportion of Δ zones created under wheel tracks. This value was estimated by the empirical relationship [8] between the relative area of Δ zones created during traffic (A) and the soil water content at the time of traffic (w) for a given field intervention (i):

$$Ai(w) = \frac{ld}{lmax, idmax} = \frac{(Wf(w) - W0)(Wd(w) - W0)}{(Wfl - W0)(Wfd - W0)}$$

With

$$W_f(w) = W_0 \text{ if } w \le W_0,\ W_f(w) = w \text{ if } W0 \le w \le W_{fl},\ W_f(w) = W_{fl} \text{ if } w \ge W_{fl}$$
$$W_d(w) = W_0 \text{ if } w \le W_0,\ W_d(w) = w \text{ if } W_0 \le w \le W_{fd},\ W_d(w) = W_{fd} \text{ if } w \ge W_{fd}$$

l is the width of the Δ zone, d the depth of the Δ zone, $l_{max,i}$ the maximum tyre width (cm) of the equipment, and d_{max} the ploughing depth (30 cm).

W_0 corresponded to the soil water content below which no Δ zone was created under the wheel (Ai(w) = 0 for $w \le W_0$). W_{fl} related to the soil water content beyond which the width of the Δ zone was equal to the maximum tyre width ($l_{\max}$). W_{fd} matched to the soil water content beyond which the depth of the Δ zone reached ploughing depth ($d_{\max}$). Therefore, Ai(w) = 1 when $w \ge W_{fd}$ and $w \ge W_{fl}$. The field interventions performed during this experiment were classified into three compaction groups, which were defined based on the ground pressure at the tyre/soil interface (front and rear wheels), calculated using the model of O'Sullivan et al. [4]. Roger-Estrade et al. [8] calibrated the three parameters W_0, W_{fl} and W_{fd} for each compaction group.

An annual compaction intensity index (ACI_n) was calculated to describe the annual compaction per experimental plot across the three CSs. We added the areas of Δ zones created by the two main wheels of each equipment part used for the field interventions relative to the area of the soil profile affected by each intervention, which depended on the working width, leading to the following formula:

$$ACIn = \sum_{i=1}^{p} 2lmax, \frac{iAi(wi)}{Lw, i}$$

Where w_i is the water content of the 0–30 cm layer measured at the i^{th} field intervention while $L_{w,i}$ is the working width of the i^{th} field intervention. The field intervention number 1

($i = 1$) corresponds to the first field intervention following the harvesting of the previous crop while the last field intervention ($i = p$) corresponds to harvesting. We did not take ploughing into account because, as two wheels of the tractor roll on the plough pan, most of the compaction forces affect the subsoil. No pesticide and fertilizer applications were taken into account as they were always located at the same place in the plot that were not concerned by field observations.

The proportion of Δ areas in year n ($P\Delta_n$) was determined as a function of the proportion of Δ areas in year - 1 ($P\Delta_{n\text{-}1}$). This was done assuming that the loss of Δ zones during an entire cropping year, between two successive crop sowings, occurred only from the surface layer of the ploughed horizon during seedbed or stubble tillage and under the influence of climate using the following formula:

$P\Delta n = (1 - \frac{dst}{dmax})P\Delta n - 1$ Where d_{st} is the maximum depth (cm) of seedbed preparation or stubble tillage during the year n - 1. This calculation was made on experimental plots where no Δ zones were created during the year n - 1 (ACI_n-1 = 0).

In Boizard et al. [3], the proportion of areas with Δ, P and Φ structures (I_Compact H5)) was calculated as the ratio of the soil structural area to the total area of the tilled layer under the seedbed. In the data sheet “Detailed data 2000-2018” of the table “5_morphological approach” of this paper, all the clods and zones are described with the different states of porosity, their size and area. The soil profiles are presented in the database with photos before (i.e. the original) and after processing using image analysis. The name of the profile in the file and the database "photos" match, as does the number of each clod in the profile.

6. Seedbed Characterization

The above-described method was not used for seedbed structure analysis because most of the soil fragments in the seedbed were too small for an appropriate determination of their internal structure. In addition, sieving such small fragments was less disturbing than sieving the underlying ploughed layer. Seedbed structure was determined by the fragment mass-size distribution. Seedbed soil samples were taken after each crop sowing from 0 to 6 cm depth in the region without wheel tracks since the last ploughing operation. The distribution of the seedbed aggregate size was characterized as described previously [9]. A surface was delimited along the row of the seedbed with combs (20 length x 10 width x 10 cm depth) to determine either the numbers, mass or percentage of aggregates or all of them in a precise soil volume. The number of replicate/year/crop ranged from 10 to 48 for SP, 16 to 24 for OR, 10 to 48 for WW, 12 to 48 for SB, and 16 to 48 for M. Soil samples from all the treatments (*i.e.* the zones subjected and non-subjected to wheel traffic from conventionally tilled plots as well as from plots with reduced tillage) were carefully extracted with a spoon, brought to the laboratory, and air-dried. The samples were sieved with a gently shaking machine (30 s, 50-mm amplitude) and grades <5, 5-10, 10-20, 20-30, 30-40, 40-50, and >50 mm diameter were obtained. The number, the mass and the volume for each of these grades were determined. In Lamichhane et al. [10], the observed variations, in terms of percentages of soil aggregates, measured for each seedbed class of crops belonging to the three cropping system, were used to define three types of seedbed structures: a fine seedbed (with >20mm soil aggregates <15%)), an intermediate seedbed (with >20mm soil aggregates >15<25%), and a coarse seedbed (with >20mm soil aggregates >25%). Data are given in the datasheet “2_seedbed aggregates”.

7. Crop Emergence Rates and Yield

The emergence rates were calculated as the ratio of the number of emerged seedlings to the theoretical sowing density. This measurement was conducted in approximately 2.50 m^2 of the sub-plot area for each crop. The theoretical number of emerged seedlings was calculated either by taking into account the inter-row spacing for crops sown with a precision seeder or by determining the quantity of seeds sown in each plot and the 1000-grain mass. The yield for each crop was measured on the whole plot every year. The total experimental area was 15 ha with the average surface of 0.40 ha/plot, ranging between 0.36 and 1.10 ha. Data are given in datasheets "6_emergence rate" and "7_data_yield".

Ethics Statement

Not applicable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships, which have or could be perceived to have influenced the work reported in this article.

CRediT Author Statement

Jay Ram Lamichhane: Data curation, Writing – original draft, Writing – review & editing; **Hubert Boizard:** Conceptualization, Methodology, Methodology, Investigation; **Carolyne Dürr:** Conceptualization, Methodology; **Guy Richard:** Conceptualization, Methodology; **Jean Boiffin:** Conceptualization, Methodology.

Acknowledgments

We thank the technical team of the INRA's domain in Mons-en-Chaussée for supporting the long-term experiment, and in particular Paul Régnier, Charles Leforestier, Daniel Boitez, Caroline Dominiarzyck, Bertrand Chauchard, Frédéric Mahut who efficiently contributed to the management of the long-term experiment and characterization of seedbed structure.

References

[1] A.R. Dexter, Advances in characterization of soil structure, Soil Tillage Res. 11 (3) (1988) 199–238 Available from: http://www.sciencedirect.com/science/article/pii/0167198788900025.
[2] H. Boizard, G. Richard, J. Roger-Estrade, C. Dürr, J. Boiffin, Cumulative effects of cropping systems on the structure of the tilled layer in northern France, Soil Tillage Res. 64 (1) (2002) 149–164 Available from: http://www.sciencedirect.com/science/article/pii/S0167198701002525.
[3] H. Boizard, S.W. Yoon, J. Leonard, S. Lheureux, I. Cousin, J. Roger-Estrade, et al., Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage, Soil Tillage Res. 127 (2013) 34–44 Available from: http://www.sciencedirect.com/science/article/pii/S0167198712000943.
[4] M.F. O'Sullivan, J.K. Henshall, J.W. Dickson, A simplified method for estimating soil compaction, Soil Tillage Res. 49 (4) (1999) 325–335 Available from: http://www.sciencedirect.com/science/article/pii/S0167198798001871.
[5] G. Monnier, P. Stengel, J.C. Fiès, Une methode de mesure de la densite apparente de petits agglomerats terreux. Application a l'analyse des systemes de porosite du sol, Ann. Agron. 24 (1973) 533–545.
[6] G. Richard, H. Boizard, J. Roger-Estrade, J. Boiffin, J. Guérif, Field study of soil compaction due to traffic in northern France: pore space and morphological analysis of the compacted zones, Soil Tillage Res. 51 (1) (1999) 151–160 Available from: http://www.sciencedirect.com/science/article/pii/S0167198799000586.
[7] H. Manichon, Observation morphologique de l'état structural et mise en évidence d'effets de compactage des horizons travaille´s, in: G. Monnier, M.J. Goss (Eds.), Soil Compaction and Regeneration, Balkema, Rotterdam, the Netherlands, 1987, pp. 39–52.
[8] J. Roger-Estrade, G. Richard, H. Boizard, J. Boiffin, J. Caneill, H. Manichon, Modelling structural changes in tilled topsoil over time as a function of cropping systems, Eur J Soil Sci 51 (3) (2000 Sep 1) 455–474, doi:10.1046/j.1365-2389.2000.00323.x.
[9] J.N. Aubertot, C. Dürr, K. Kieu, G. Richard, Characterization of sugar beet seedbed structure, Soil Sci. Soc. Am. J. 63 (1999) 1377–1384, doi:10.2136/sssaj1999.6351377x.
[10] J.R. Lamichhane, J. Boiffin, H. Boizard, C. Dürr, G. Richard, Seedbed structure of major field crops as affected by cropping systems and climate: Results of a 15-year field trial, Soil Tillage Res. 206 (2021) 104845, doi:10.1016/j.still.2020.104845.