

A hybrid method for characterizing tillage-induced soil physical quality at the profile scale with fine spatial details

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ABSTRACT

Robust methods are needed to assess tillage-induced changes in the physical quality of agricultural soils. Most soil physical quality (SPQ) evaluation procedures are based on the analysis of a limited number of soil cores randomly sampled in the soil profile. Such procedures likely fail to properly capture the spatial patterns in soil structure induced by tillage implements and vehicle traffic, resulting in a misleading SPQ diagnosis. We propose a hybrid method that couples high-resolution soil penetration resistance measurements with soil core sampling to derive high-resolution data grids of SPQ indicators encompassing the soil profile structural heterogeneity. The method builds on strong experimental relationships between soil penetration resistance and bulk density, and between bulk density and the soil hydraulic properties. We tested our method on a silt-loam soil with three tillage treatments (moldboard plowing, deep loosening with a tine cultivator, and minimum tillage), each including a zone impacted by the wheel traffic. The results allow visualization and analysis of the effect of tillage treatments and vehicle traffic on the soil SPQ indicators with a high level of spatial detail. The proposed methodology can be used to compare various soil management techniques or to monitor the temporal evolution of SPQ. As such, it can be a valuable tool to guide agricultural soil management. Furthermore, the generated high-resolution soil physical parameter grids could be used to parameterize numerical hydrodynamic models and estimate water and solute fluxes with distributed parameters representing the actual soil profile heterogeneity.

1. Introduction

Healthy agricultural soils are fundamental to ensure sustainable food production for humans and animals, to control soil erosion, and to protect groundwater and surface water from pollution. Yet, these soils are exposed to considerable pressures due to intensification of agricultural practices, threatening their ability to perform their services and environmental functions sustainably (Hamza and Anderson, 2005; Matson et al., 1997; Smith et al., 2016).

Soil quality monitoring is an essential step to assess the impact of agricultural practices. A plethora of field or plot-scale soil quality

assessment and monitoring procedures have been proposed as tools and guidelines for agricultural management and as scientific basis for policymaking (reviewed in Bünemann et al., 2018). Methods mainly rely on visual inspection of soil profiles (reviewed in Emmet-Booth et al., 2016) or soil sampling and analysis. Several procedures exist for the latter. Soil quality analysis can be based on a specific set of indicators of the soil attributes, sometimes associated with target ranges and scoring functions (Karlen et al., 1997; Lilburne et al., 2002, 2004; Reynolds et al., 2002, 2009). Other procedures are based on an integrative soil quality indicator such as the S-index (Dexter, 2004b, 2004a), or on an extended list of candidate indicators from which users can select a relevant set

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based on the ecosystems services or soil management objectives to be assessed (Andrews et al., 2004; Karlen et al., 2001; Wienhold et al., 2009). Statistical approaches such as principal component analysis are also widely used as a reduction technique to identify a minimum dataset that adequately serves the specificity of the soil and assessment goal. The indicators proposed are designed to assess the soil physical, chemical, and biological attributes (Bünemann et al., 2018) that define the overall soil health.

In this article, we focus on the soil physical quality (SPQ) component of soil health, of which soil structure is a key factor (Pagliai and Vignozzi, 2002; Rabot et al., 2018). By soil structure, we mean the shape, size and spatial arrangement of primary soil particles and aggregates, and the resulting pore network. It is defined by abiotic (e.g., pH, carbon content), biotic (e.g., root, soil organisms) and management-related (e.g., tillage) factors and covers a range of scales, typically from micrometric to decametric scales. It controls rooting conditions, air and water fluxes and stocks, and regulates the habitat for soil organisms.

A variety of procedures and approaches have been developed to assess the SPQ. Penetration resistance (PR) is commonly used to study soil resistance to root growth (Bengough and Mullins, 1991; Bengough and Mullins, 1990; Shierlaw and Alston, 1984) and to measure the profile- or field-scale spatial distribution of soil mechanical strength (Alesso et al., 2020). Others have combined PR measurements with sample-derived soil properties such as bulk density (BD), soil water content and soil saturated hydraulic conductivity (Ks), or with crop yield, to study the effects of agricultural practices such as vehicle traffic, different tillage operations, cover crops or organic amendments (Chan et al., 2006; Dada et al., 2021; Gabriel et al., 2021; Souza et al., 2020; Stošić et al., 2020; Tester, 1990). PR is usually measured at various locations along a transect or at scattered locations across an agricultural field, and at 2 or 3 depths in the topsoil horizon. Another commonly used approach is to derive SPQ indicators from a limited number of disturbed or undisturbed soil cores sampled in the topsoil (e.g., Andrews et al., 2002; Gong et al., 2015; Liu et al., 2018; Zhao et al., 2017). These procedures ignore the horizontal and vertical patterns in soil structure induced by soil management practices such as vehicle traffic and tillage. Tillage tools modify the structure in various ways depending on the type of tillage implement. This creates a structural heterogeneity in the direction perpendicular to the displacement direction of the tillage implement, dictated by the configuration of the tillage tools (Coquet et al., 2001; Destain et al., 2015, 2016; Hubert H. Manichon and Gautronneau, 1987; Hubert Manichon and Gautronneau, 1987; Roisin, 2007). Examples are the minimum or reduced tillage techniques using tines as soil perturbation varies with the distance from the tine. By drastically influencing the water and air storage and fluxes (Besson et al., 2011; Gerke and van Genuchten, 1993; Jarvis et al., 2013; Smettem and Kirkby, 1990; Tuller and Or, 2002), this management-induced soil structural heterogeneity impacts root growth and biological activity and, consequently, the SPQ. A soil sampling strategy that is not representative of the structural patterns at the profile scale – here defined as a soil section perpendicular to the direction of the vehicle traffic and sufficiently large to encompass the micrometric to decimetric-scale soil structure variability created by agricultural soil management practices – is, therefore, likely to lead to inaccurate conclusions regarding the SPQ.

Various methods have been proposed to study the effect of agricultural practices on such structural variability at the profile scale. Manichon and Gautronneau (1987); Hubert Manichon and Gautronneau (1987) developed the trench-based “profil cultural” method for a 2-D, qualitative in-situ description of soil structural patterns. PR measurements taken at a fine spatial resolution and geophysical methods such as electrical resistivity or ground penetration radar have also been successfully used across similar scales for characterizing the soil heterogeneity in 2D or 3D (Roisin, 2007), revealing soil structural units (Boizard and Richard, 2004; Jerábek et al., 2017; Jonard et al., 2013; Séger et al.,

2009) or quantifying soil moisture variability (Binley et al., 2015). While they provide critical information about the organization of the structural units and variability in soil strength, these techniques do not allow calculating the SPQ indicators commonly derived from a soil sampling approach. In this study, we propose a method to bridge that gap. Our objectives are (i) to develop a method for the assessment of physical quality of agricultural soils that takes into account the soil profile heterogeneity; and (ii) to illustrate the method by evaluating the effect of different tillage practices and wheel traffic on SPQ.

2. Materials and methods

Our method relies on the existence of a relationship between soil bulk density (BD) and penetration resistance (PR) (Quraishi and Mouazen, 2013) and between BD and soil hydraulic parameters (Verbeeck et al., 2007; Weynants et al., 2009; Wösten et al., 2001), and builds on two types of field measurements. The first is the soil resistance to penetration at the profile-scale at high spatial resolution (gridded data of 5 cm interpolated to 1 cm resolution in the horizontal plane and 1 cm vertical resolution). The second type of measurement is soil core sampling at various locations in a soil profile from which we derived point-scale soil BD and hydraulic parameters. We then used the field measurements to establish empirical site-specific relationships between (i) BD and PR; and (ii) hydraulic parameters and BD. Next, we used the relationships to generate high-resolution data grids of BD from the PR data grids and high-resolution data grids of the hydraulic parameters from the BD grids. Finally, we used these grids to compute a set of indicators of SPQ as proposed in Reynolds et al. (2002)). To assess the effect of soil tillage and vehicle traffic, we repeated the procedure on three agricultural plots prepared with three different soil tillage practices, each including a wheel track. The methodological flowchart is given in Fig. 1 and detailed below.

2.1. Data collection

2.1.1. Field sites and experimental design

Field data were collected during three consecutive years in three experimental agricultural fields located in Gentinnes (Fields A and B; 50.588°N - 4.594°E, and 50.572°N - 4.596°E, respectively) and Mont-Saint-Guibert (Field C; 50.626°N - 4.598°E), Belgium. The climate is temperate, with a mean annual rainfall of 852 mm and a yearly average temperature of 10.5 °C. Soil texture is silt loam (~ 18% clay, 75% loam, 7% sand) for Fields A and B, and loamy-sand (~ 12% clay, 75% loam, 13% sand) for Field C. These sites were chosen because they are representative of the dominant soil types of the Belgian loess belt used for intensive cropping, and because of on-going experiments by the Walloon Agricultural Research Center (CRAW) comparing different tillage techniques. Each agricultural field included plots that underwent different soil tillage treatments: moldboard plowing (MP) to a depth of 27 cm, which corresponds to the conventional way of tilling the soil in the area; deep loosening (DL) with a rigid straight tine subsoiler with vanes (6 tines over a 3 m bar) to a depth of 32 cm; or minimum tillage (MT) using a spring-tine cultivator to a depth of 10 cm. The tillage took place in early September after which a cover crop was grown and removed with application of glyphosate at the end of the winter. The soil was then prepared superficially with a rotative harrow after which the next crop was sown. Sowing involved one pass for wheat and two for sugarbeets. In Fields A and B, the treatments were laid out following a Latin square design with three 18 × 40 m (Field A) or 18 × 30 m (Field B) replicate plots per treatment. In Field C, the treatments were applied on land strips parallel to the vehicle traffic direction and dividing the field in three equal-size plots. The main crops were wheat (*Triticum aestivum* L.) grown in rotation with sugarbeets (*Beta vulgaris* L.) (Table 1).

We conducted measurements within 1.6 m × 4 m zones in each plot, further referred to as “experimental subplots”. These subplots were located near the borders of the fields while avoiding any edge effect.

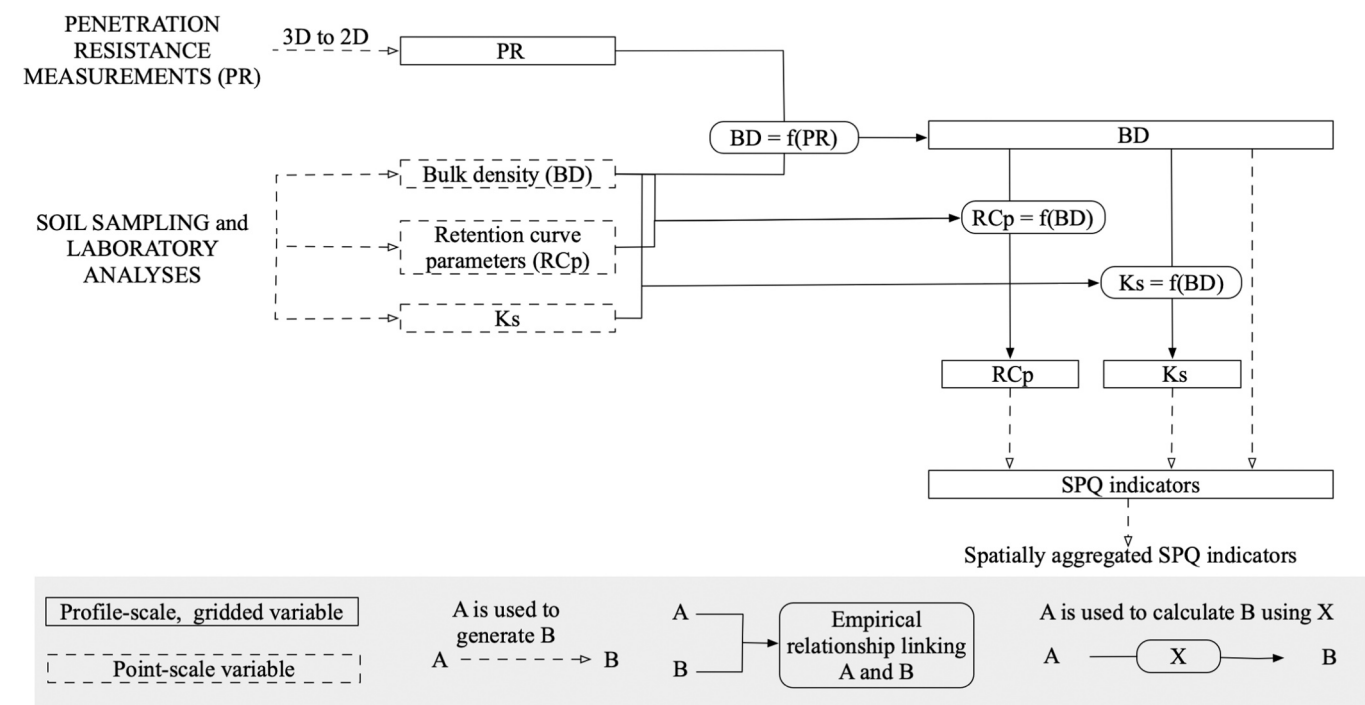


Fig. 1. Methodological flowchart.

Table 1
Crop and treatment calendar for each field. MP: Moldboard plowing; DL: deep loosening; MT: minimum tillage.

Year	Field A - Patriote		Field B - Champ du Mont		Field C - Dolphens	
	Treatment	Crop	Treatment	Crop	Treatment	Crop
< 2004	MP	NA	MP	NA	NA	NA
2004	MP	Potatoes	MP	NA	NA	NA
2005	MT	Wheat	MP	Potatoes	NA	NA
2006	MP, MT, DL	Sugarbeets	MT	Wheat	NA	NA
2007	MP, MT ^a	Wheat	MP, MT, DL	Sugarbeets	NA	NA
2008 (Year I)	MP, MT, DL	Sugarbeets	MP, MT ^a	Wheat	MT	Maize
2009 (Year II)	MP, MT ^a	Wheat	MP, MT, DL	Sugarbeets	MP	Wheat
2010 (Year III)	MP, MT, DL	Flax	MP, MT ^a	Wheat	MP, MT	Sugarbeets

NA: information not available
^a In years during which wheat was grown, plots initially in DL were treated with MT.

Each subplot included a wheel track occupying about half of its width (Fig. 2). The wheel track was trafficked by the vehicles during soil preparation, sowing, and harvest, whereas pesticides and fertilizers were applied by vehicles circulating outside of these subplots. We conducted the measurements in each field over one or two consecutive days

and at the beginning of the spring when the soil was bare and its water content was expected to be near field capacity. Details on the measurements conducted each year and their use for further analyses are given in Table 1.

2.1.2. In-situ measurements

2.1.2.1. Soil penetration resistance measurements. We performed soil penetration resistance (PR) measurements on each experimental subplot with a fully automated penetrometer (30° angle cone with a base area of 1 cm²) mounted on a small vehicle as described in Roisin (2007). The measurements covered an area of 1.6 m (x-axis, perpendicular to tillage direction) x 0.8 m (y-axis, in the tillage direction; Fig. 2). Previous studies have shown such an area to be sufficiently large to evaluate the effect of soil tillage and traffic on the soil physical properties (Roisin, 2007). We took the measurements along a 5 cm resolution grid within the 1.6 m x 0.8 m horizontal plane and between 0 and 45 cm depth at 1-cm increments, which led to 28,611 data records for each subplot. Assuming that the variability of soil resistance and hence PR were small along the soil tillage direction (y-axis) compared to the perpendicular direction (x-axis), we averaged each data array along the y-axis, resulting in 2 dimensional vertical grids of 5 cm resolution in the x-axis,

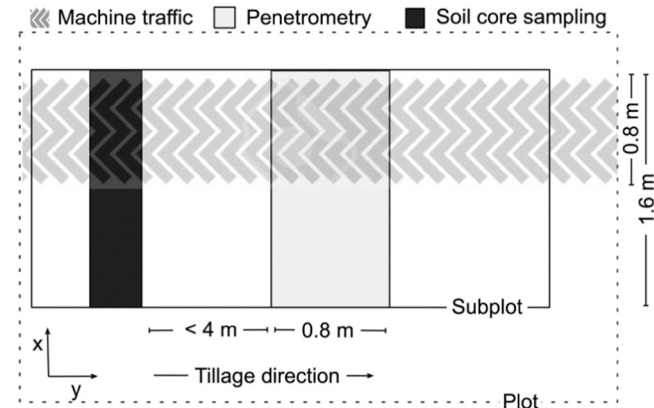


Fig. 2. Schematic representation of an experimental subplot.

and 1 cm resolution along depth (z-axis). We then carried out linear interpolation to generate PR data grids with a 1 cm resolution in the x and z axes. We refer to the resulting data as the “2D PR measurements”. The PR sensor threshold was 100 kg/cm². Higher values were dismissed as they cannot be reliably interpreted.

2.1.2.2. Soil profiling and sampling. Immediately after the PR measurements, we dug 1.6 m wide x 0.5 m deep pits perpendicular to the soil tillage direction and within a 4 m distance from the PR measurement areas (Fig. 2). We performed an in-situ analysis adapted from a methodology developed by Manichon (H. Hubert Manichon, 1987; H. Manichon, 1987; Manichon and Gautronneau, 1987; Hubert Manichon and Gautronneau, 1987) to delineate within the soil profiles the dominant soil structural units such as clods and compacted zones (Fig. 3). First, we identified the soil layers created by successive soil tillage operations. Within those layers, zones were classified in three classes based on their relative structural porosity from compacted soil with no structural porosity (similar to Delta-type clods in Manichon’s method) to soil with the highest observed structural porosity (similar to Gamma-type clods in Manichon’s method).

We then sampled 12–15 undisturbed 100-cm³ soil cores using Kopecky rings of 51 mm height and 50 mm diameter for bulk density and water retention curve determination. We also sampled 49 additional undisturbed soil cores using the same Kopecky rings for Ks measurements (Table 1). Sampling locations were selected across the entire profile while covering the variety of structural units identified during soil profile description.

2.1.2.3. Crop yield. We determined the average yield of the sugarbeets for each treatment and for Field A during Year I. The sugarbeets were harvested one month before their full maturity as harvest had to be manual and dependent on the weather conditions.

2.1.3. Ex-situ soil bulk density and hydraulic properties measurements

We calculated the bulk density of the undisturbed soil cores collected in Fields A, B, and C during Year II and Year III by dividing their weight W_{dry} after oven-drying during 48 h at 105 °C by their volume (100 cm³).

We measured the volumetric soil water content of these samples after reaching equilibrium at increasing levels of suction using the relation in Eq. (2):

$$\theta_v(h) = \frac{(W_h - W_{dry})/\rho_w}{V} \quad (1)$$

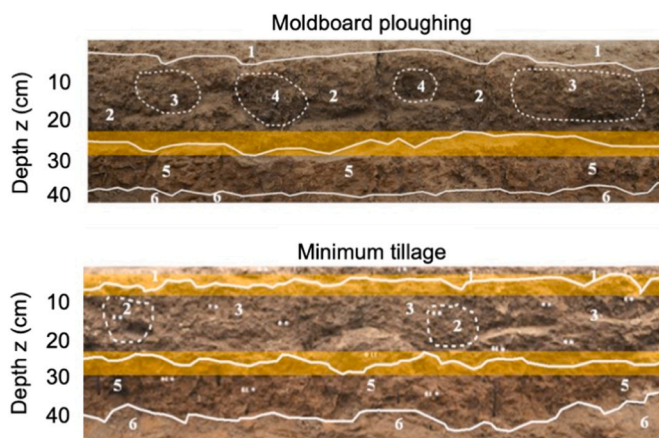


Fig. 3. Illustration of soil profiles descriptions in moldboard ploughing and minimum tillage treatments illustrating the Manichon method used to select soil sampling locations representative of the soil structural heterogeneity. 1: Seed bed; 2–4: intermediate soil layer between the seed bed and the plough pan, with structural porosity ranging from high (2) to nil (4); 5: plough pan; 6: B horizon.

where $\theta_v(h)$ and W_h are the soil water content (cm³ cm⁻³) and the weight (g) of soil core at matric potential h , ρ_w is the water density set at 1 g/cm³, and V is the soil core volume, here 100 cm³. We used a sandbox apparatus (® Eijkelkamp) for applying suction levels (h) equal to 1, 10, 31, and 63 cm (pF0, 1, 1.5, and 1.8 respectively), and low and high-pressure chambers (® Eijkelkamp) for suctions equal to 100, 310, and 1000 cm, and 3100, 10000 and 13,100 cm (corresponding to pF 2, 2.5, 3, and 3.5, 4 and 4.1), respectively. We then determined the water retention parameter sets for each sample by fitting van Genuchten’s equation (Eq. (4), van Genuchten, 1980):

$$\theta_v(h) = \theta_{v,r} + \frac{\theta_{v,s} - \theta_{v,r}}{(1 + (\alpha|h|)^n)^m} \quad (2)$$

where h is the soil matric head (cm), $\theta_v(h)$, $\theta_{v,r}$ and $\theta_{v,s}$ are the volumetric water content values at matric head h , residual, and at saturation, respectively (cm³ cm⁻³), and α (cm⁻¹), n (-), and $m = 1 - (1/n)$ (-) are empirical curve-fitting parameters. We constrained the values of $\theta_{v,r}$ to 0. We used the *fminsearch* function, a nonlinear programming solver in Matlab (Matlab, 2018) that uses the simplex search method of Lagarias et al. (1998) to search for the parameter combination that minimizes a user-defined objective function, here defined as the root mean square error. To orient the search in the parameter space, we set the initial values for $\theta_{v,s}$, α , and n parameters to 0.3, 0.5, and 1, respectively.

We eliminated anomalous water retention curves with a visual inspection of the plotted experimental data points based on the following criteria: (i) non-monotonic decrease in water content with increasing suction; or (ii) the water content at pF0 was higher than the porosity calculated using Eq. (3) where ρ_s is the soil particle density estimated at 2.65 g/cm³ and ϕ is the porosity (cm³/cm³):

$$\phi = 1 - BD/\rho_s \quad (3)$$

We measured saturated hydraulic conductivity (Ks) on undisturbed Kopecky rings (100 cm³) with a constant head permeameter (® Eijkelkamp).

2.2. Generation of high-resolution profiles of soil variables and indicators of SPQ

2.2.1. BD – PR Relationship

We paired the BD of each soil sample with the 2D PR measurements averaged over a five-by-five cm square centered on the coordinates (x, z) of the soil sample. We then modeled the relationship of the BD-PR pairs with ordinary least squares regressions. We found that, for this case study, the fields and soil types did not significantly affect the empirical BD = f(PR) relationships. Therefore, we combined the BD-PR points from the six experimental subplots for which soil had been sampled (Table 2) – leading to 86 samples in total – and derived a unique relationship. We fitted the regression model successively for each 1-cm depth increment by selecting the PR-BD pairs whose z-coordinate was included within a [– 5 cm, + 5 cm] depth interval. The reasons for using a depth-adjusted model were to account for the effect of the overburden pressure and possibly also a vertical gradient in moisture or organic carbon content (Blanco-Canqui et al., 2006; Latvala et al., 2020; Wang et al., 2021). We found that the relationship between BD and PR could be linearized using a transformation as follows:

$$BD_{xz}^2 = a_z * \ln(PR_{xz}) + b_z \quad (4)$$

where BD_{xz} and PR_{xz} are the bulk density and penetration resistance at (x, z) coordinate, and a_z and b_z are regression coefficients whose values change with depth z.

2.2.2. Relationships between hydraulic parameters and BD

We carried out regression analyses to model the relationship between BD and the van Genuchten water retention curve parameters (Eq. (4)), and between the BD and saturated hydraulic conductivity. All

Table 2

Experimental set-up. MP: moldboard plowing; DL: deep loosening; MT: minimum tillage. Star (*) symbol indicates that the experiment or computation was conducted for the corresponding subplot.

Year	Field ID and local name	Soil prep	Nb of PR profiles	Profile ID	BD	RC	Ks	Empirical relationships		Used to generated BD data grids and calculate SPQ indicators	Crop yield
					(Number of soil samples)			BD = f (PR)	RC&Ks = f (BD)		
I	A - Patriote	MP	3	A1MP1-3	0	0	0	/	/	*	*
I	A - Patriote	DL	3	A1DL1-3	0	0	0	/	/	*	*
I	A - Patriote	MT	3	A1MT1-3	0	0	0	/	/	*	*
II	B - ChdM	MP	1	B2MP	16	0	0	*	/	/	/
II	B - ChdM	DL	1	B2DL	16	0	0	*	/	/	/
III	C - Dolphens	MP	1	C3MP	15	15	20	*	/	/	/
III	C - Dolphens	MT	1	C3MT	12	12	0	*	/	/	/
III	A - Patriote	MP	1	A3MP	13	13	14	*	*	/	/
III	A - Patriote	MT	1	A3MT	14	14	15	*	*	/	/

linear regressions were conducted with the *fitlm* function in Matlab (Matlab, 2018).

2.2.3. Upscaling at the profile scale and computation of the SPQ indicators

We used the empirical relationships to generate high-resolution grids of BD and a set of SPQ indicators. We used a suite of indicators of the soil air and water storage necessary for crop growth and impedance to root growth, as proposed in (Reynolds et al., 2009). The indicators' names, definitions, and the physical properties they measure are listed in Table 3. Additionally, we considered the saturated hydraulic conductivity (Ks) and the homogeneity index (I_h). The latter indicates the local variation of the soil structure calculated from the penetration resistance

Table 3

Indicators used for the soil physical quality assessment.

Indicator, symbol and unit	Indicator definition	Soil physical quality property measured
Saturated hydraulic conductivity, Ks (cm.s ⁻¹)		Ease with which pores of a saturated soil transmit water
Bulk density of total soil, BD (g.cm ⁻³)	Mass of dry soil solids per unit bulk soil volume	Index of soil strength. Also used to obtain the other indicators.
Porosity of soil macropore domain POR _p (m ³ .m ⁻³)	POR _p = $\theta(h=0) - \theta(h=-10 \text{ cm})$	Volume of soil pores with equivalent diameters $\geq 300 \mu\text{m}$ (soil macropores) indicating the soil's ability to quickly drain excess water and facilitate root proliferation.
Air capacity of total soil AC _t (m ³ .m ⁻³)	AC _t = $\theta(h=0) - \theta(h=-100 \text{ cm})$	Index of soil aeration on total soil volume basis
Plant available water capacity, PAWC (m ³ .m ⁻³)	PAWC = water content at field capacity (FC) - water content at permanent wilting point = $\theta(h=-100 \text{ cm}) - \theta(h=-1.5 \times 10^4 \text{ cm})$	Soil water readily available for crop growth
Relative field capacity RFC (-)	RFC = FC / θ_{sat}	Soil's ability to store water and air relative to the soil total pore volume
S-value	Slope of the soil water retention curve at the inflection point, calculated as:	Indicator of overall quality for crop growth
	$S = n(\theta_{\text{sat}} - \theta_r)$	
	$\left[\frac{2n-1}{n-1} \right] \left[\frac{1}{n} - 1 \right]$	
Homogeneity index I _h	Based on penetration resistance data. See Roisin (2006) for details.	Structural homogeneity of soil layer

$\theta(h)$ = volumetric soil water content as a function of pore water pressure head h

Source: Adapted from Reynolds et al. (2002).

measurements, which is useful to quantify the soil profile heterogeneity (Roisin, 2007). We did not consider organic carbon content and structural stability index, two indicators in the suite proposed in (Reynolds et al., 2009), because of data limitation.

To evaluate the effect of treatment and vehicle traffic on SPQ, we assessed the indicator values in relative terms (lower than or greater than). We also compared the values to ideal ranges and critical values reviewed in Reynolds et al. (2009) to reflect on the soils' actual quality level.

2.3. Assessment of soil profile heterogeneity and SPQ

We tested the effect of soil tillage and traffic on the SPQ indicators using four data visualisation and analysis methods. The first was the visual observation and characterization of the spatial variability of the 2D profiles of indicators derived from the PR measurements. The second was the probability density estimates of the indicators with a normal kernel function. The third was the spatially-averaged indicator values and their visualisation in radar plots. Each spoke in the radar plot represents an indicator and is bounded by the minimum and maximum indicator values among all the profile repetitions. The areas delineated by the radar plots are indicative of the SPQ of a treatment relative to the SPQ of the others, a larger area being indicative of a relatively higher SPQ and conversely. Lastly, we also tested the significance of the treatment and traffic effects for each indicator with 2-way analyses of variance (ANOVA). For all these analyses, we used the data generated from the PR measurements conducted on Field A during the Year I since the availability of repetitions for each treatment allowed for a more robust assessment (Table 1).

We calculated the effective Ks ($K_{s,eff}$) following Eq. (5):

$$K_{s,eff} = \frac{1}{N} \sum_{i=1}^N \frac{\sum_{j=1}^d z_j}{\sum_{j=1}^d K_{s,ij}} \quad (5)$$

where $K_{s,eff}$ is the effective Ks; N and d are the total numbers of points along the x and z-axis, respectively, z_j is the depth (cm) and $K_{s,ij}$ is the Ks at the corresponding depth at location (x_i, z_j). We calculated a simple arithmetic mean for all the other indicators. Because of a methodological limitation explained in the Results section, we only considered the Ap horizon set at 0–25 cm depth, which corresponds approximately to the maximum depth of tillage for MP and DL. When relevant, we separated the zone being affected by vehicle traffic (referred to as “trafficked”) from the zone with no vehicle traffic (referred to as “non-trafficked”).

3. Results

3.1. Generation of high-resolution profiles of soil variables and indicators of SPQ

3.1.1. BD – PR relationship

Pictures of two soil profiles and the main structural units identified for the soil sampling are shown in Fig. 3. Final sample locations in the soil profile are shown in Supplementary Material, Fig. S1. The BD-PR regression models are shown for each depth in Fig. 4. The regression coefficients a_z and b_z and the corresponding coefficients of determination are shown in Fig. 5 and Supplementary Material, Table S1. Results

show that, until 25 cm depth ($z = 25$ cm), the slope coefficients a_z are different from 0 at the $p = 0.05$ significance level and are steadily increasing with depth, while the intercepts b are decreasing. The regression models until such depth lead to acceptable prediction power (adjusted coefficient of determination r^2 between 0.30 and 0.75). Therefore, a_z and b_z can also be modeled as a function of depth with the following linear regressions:

$$a_z = 0.03 * z + 0.25 \quad (6)$$

$$b_z = -0.20 * z + 1.74 \quad (7)$$

where z is the depth in centimeters. Beyond 25 cm depth, the high level

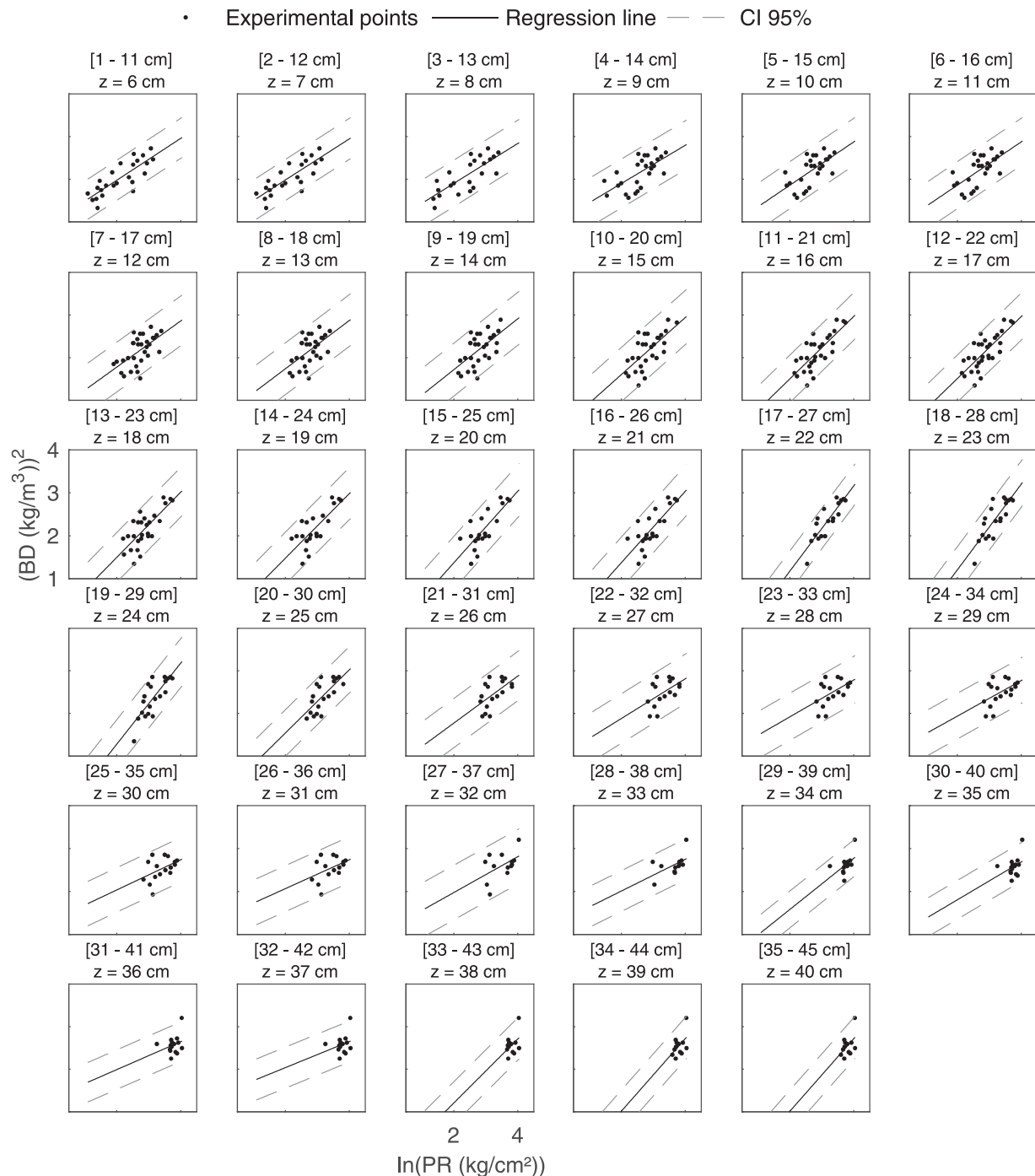


Fig. 4. (PR Relationship between bulk density (BD) and penetration resistance (PR) for data points included within a 10 cm sliding window moving along soil depth. The outer bounds of the sliding windows and the assigned depth z are indicated in the box titles. CI: confidence interval.

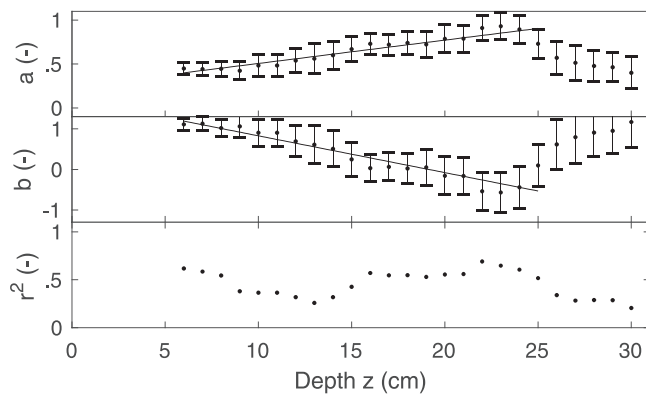


Fig. 5. Regression coefficients (a , b) and standard error bars of the relationships between the bulk density and the penetration resistance for each depth as shown in Fig. 4, and resulting adjusted- coefficient of determination (r^2). Also shown are the fitted linear regressions of a and b as a function of depth for depths between 6 and 25 cm.

of soil compaction resulted in reduced variability in the PR values (Fig. 4), preventing the establishment of any reliable $BD = f(PR)$ relationship. Therefore, we considered the depth-adjusted $BD = f(PR)$ relationship to be valid until 25 cm depth. When considering lower depths, we took the values of a_z and b_z corresponding to those at 25 cm depth. Because of that limitation, most results presented hereafter are limited to 0–25 cm depth that corresponds approximately to the Ap horizon and the maximum depth of tillage for the MP and DL treatments. The top 5 cm were modeled with the relationship established from experimental points included within the 1–11 cm depth range (i.e., for $z = 6$ in Eqs. (5) and (6)). The BD values predicted with our model versus measured BD are shown in Fig. 6A, and the error as a function of depth is shown in Fig. 6B. The root mean square error (RMSE) is 0.09 g cm^{-3} .

3.1.2. Relationships between hydraulic parameters and BD

3.1.2.1. Retention curve. The data cleaning led to the exclusion of ten and six samples from Fields A and C, respectively, which yielded 17 (θ, h) records for Field A and 21 (θ, h) records for Field C. The summary statistics of the hydraulic parameters obtained by inversion are provided in Supplementary Material, Table S2. The experimental data points and fitted models are shown in Supplementary Material, Figs. S2 and S3. A first iteration to fit a linear regression model on each parameter (n , α , θ_s) as a function of BD showed that a constant n value equal to the mean was outperforming a regression model of the type $n = f(BD)$. It also showed that the slopes and intercepts of the regression lines were significantly different between Fields A and C. Consequently, these two fields had to be treated separately. The next steps focused only on the data from Field A since the final SPQ indicators are derived from PR datasets measured in that field during Year I (Table 1). The reason for using that field is because the three repetitions per treatment allowed for statistically robust analyses. We re-iterated the inversion by constraining the value of the n parameter to 1.21, i.e., the average of the n values obtained during the first iteration for Field A. The close fit between the modeled and measured data across the full section range illustrates that constraining n did not prevent van Genuchten's equation from performing reliably (Fig. S2 in Supplementary Material). To avoid slightly negative values when predicting α from the BD in the case of high BD values, we fitted the regression model after first taking the base10-logarithmic values of α . The experimental relationships between the parameters and BD are plotted and defined in Fig. 7. Adjusted coefficients of determination (r^2) for α and θ_s are 0.53 and 0.72, respectively, with p-values ≤ 0.001 .

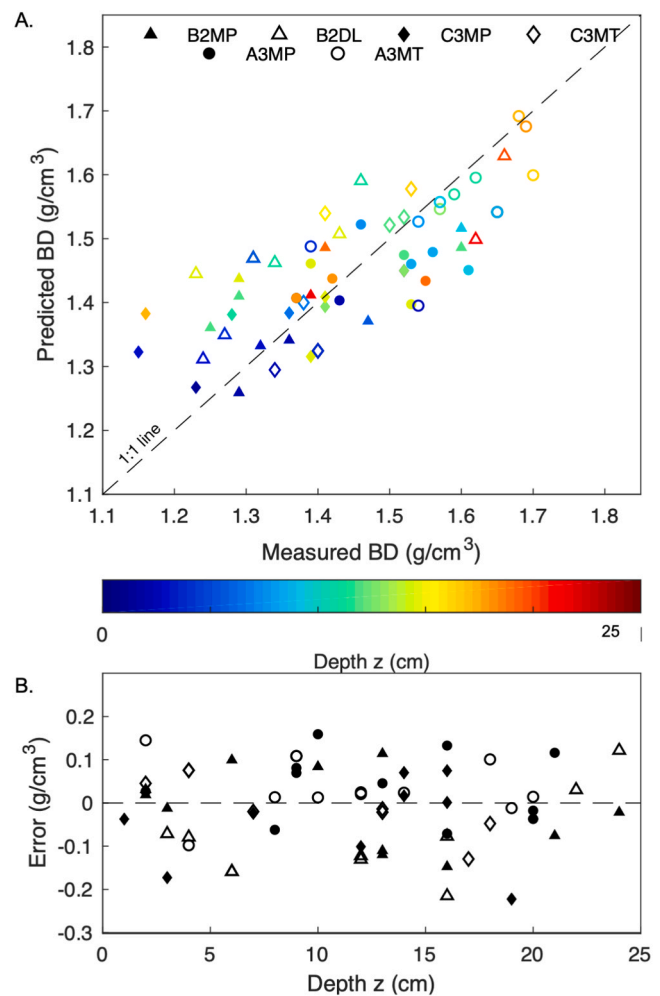


Fig. 6. A. Predicted versus measured bulk density (BD) (first 25 cm depth). B. Error between predicted and measured BD as a function of depth. The legend refers to the fields and treatments from which the samples were collected. A: Patriote; B: Champ du Mont; C: Dolphens; MP: moldboard ploughing; DL: deep loosening; MT: minimum tillage. 2: Year II, and 3: Year III.

3.1.2.2. Saturated hydraulic conductivity. Summary statistics of K_s values are given for Fields A and C in Supplementary Material, Table S2. The experimental data and relationships between the $\log_{10}(K_s)$ and BD are plotted and defined in Fig. 7. For the same reason as above, data were singled out for Field A. The relationship between K_s and BD was weak (adjusted $r^2 = 0.27$) but significant (p-value = 0.02).

3.2. Assessment of the soil profiles heterogeneity and SPQ

Fig. 8 exemplifies three grids of BD generated from PR datasets measured from experimental subplots that underwent distinct soil treatments in Field A during Year I. The figure allows for spatially explicit observations of the effect of the soil treatments and wheel traffic on the soil heterogeneity. BD in MP is relatively low throughout the Ap horizon (Fig. 8A), while the MT profile exhibits a rapid linear increase in BD with depth (Fig. 8C). Marks from tines are clearly visible around 25 cm depth in the DL treatment (Fig. 8B). The distance between each tine mark is often smaller than the 50 cm spacing between the tines. This discrepancy is due to slight shifts in the wheel track from one year to another, illustrating a “soil memory” effect. Finally, the zone impacted by vehicle traffic exhibits relatively higher BD values, which indicates a compaction effect. That effect is least visible in the MT treatment (Fig. 8C). The compacted zone is larger than the 60 cm width of the tires, which results from slight shifts in wheel tracks from one year to another

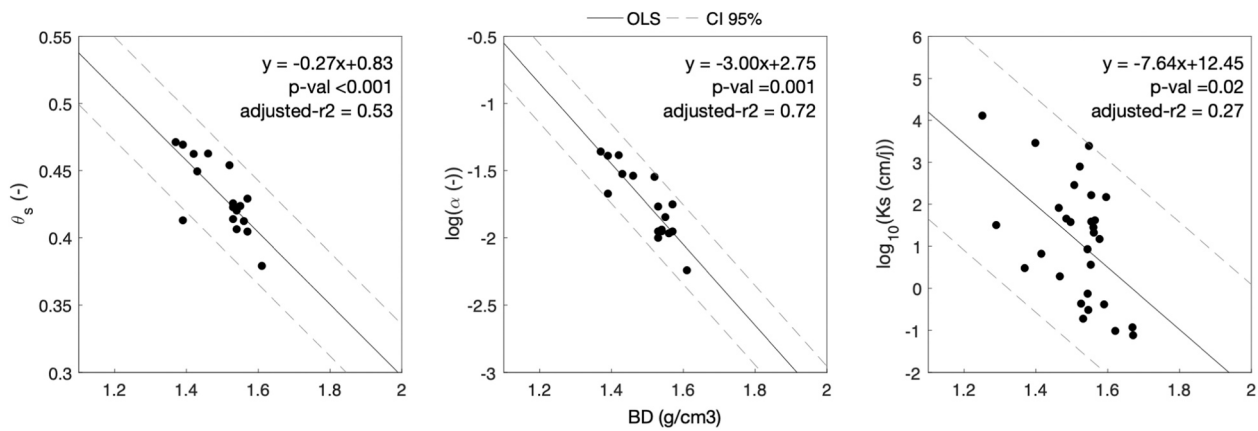


Fig. 7. Van Genuchten's equation parameters $\theta_{v,s}$ and α , and lab-measured saturated hydraulic conductivity (Ks) as a function of bulk density (BD). OLS: Ordinary Least Square regression line; CI: confidence interval at 95%.

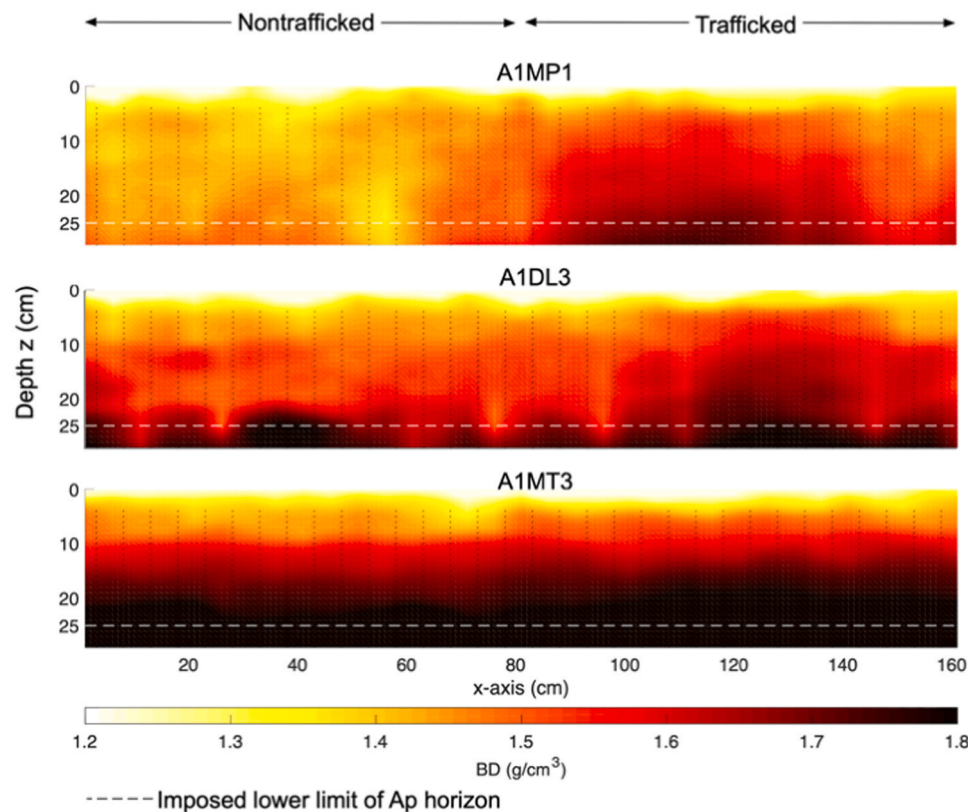


Fig. 8. Examples of soil bulk density profiles for different soil management treatments in Field A (Year I) (MP: moldboard ploughing; DL: deep loosening; MT: minimum tillage).

and is another indication of the soil's memory. In other words, the effects of compaction seem to persist despite annual tillage.

The kernel density estimations plotted in Fig. 9 shows the distributions of the values taken by the SPQ indicators in the trafficked and non-trafficked zones. The figure shows that, for the non-trafficked zones, the average distributions for MP and DL treatments are relatively similar and differ markedly from the MT treatment. Notably, while the plant available water capacity (PAWC) distribution is centered on values around 0.22 for MP and DL profiles, revealing a relatively homogeneous profile for that indicator, the distribution for the MT profiles is much more spread. Visual observation of the data profiles indeed reveals a vertical gradient of this indicator for the MT profiles (not shown). The shaded areas in Fig. 8 also reveal large inter-plot variability of the

indicator values in MP and, to a lesser extent, DL, while the variability for MT is much smaller. Finally, Fig. 8 shows that the distributions between treatments are more similar in the zones impacted by vehicle traffic, suggesting that the wheel tracks tend to cancel the benefit of soil tillage on the SPQ.

The areas delineated in the radar plots (Fig. 10) indicate that the soil tillage practice leading to the best SPQ for crop growth is MP, followed by DL and MT. These results concur with the sugarbeet yield that is higher in MP than DL and in DL than MT at the 0.001–0.1 significance level (Supplementary material, Table S4). The soil affected by traffic exhibits an overall lower quality in the MP and DL treatments, while vehicle traffic did not further degrade the soils in the MT treatment. Overall, MT shows low SPQ relative to the MP and DL treatments.

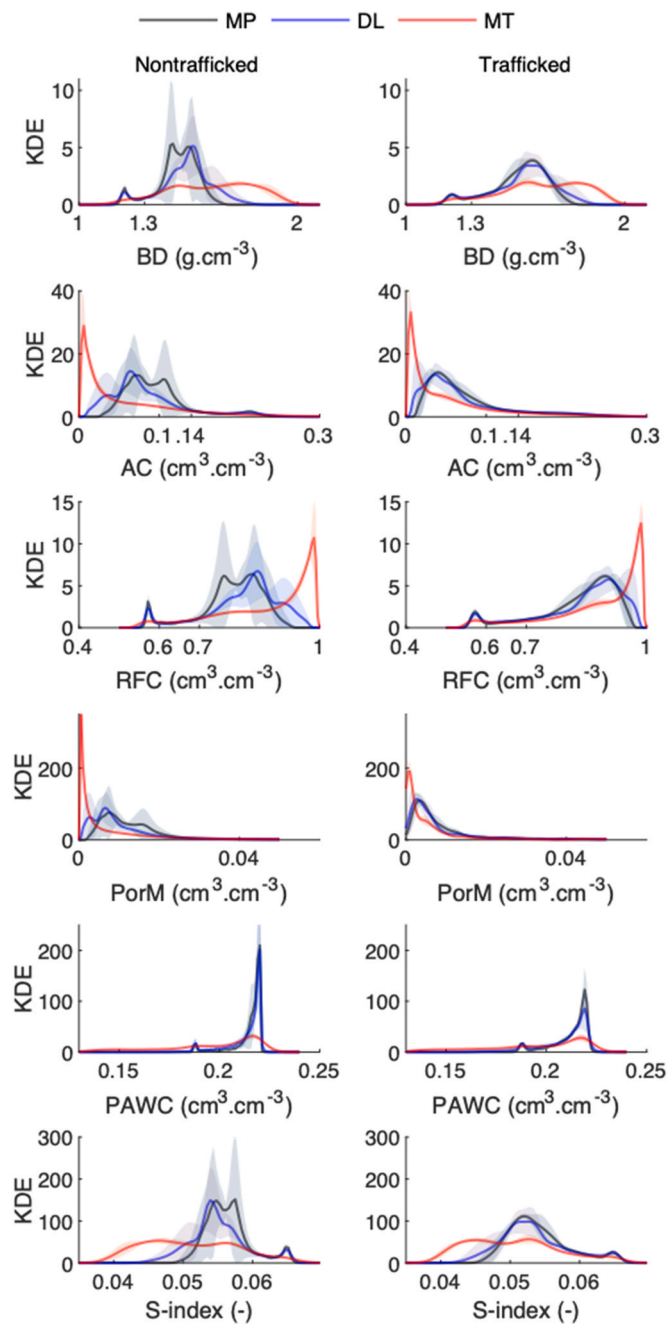


Fig. 9. Kernel density estimation of the SPQ indicators for different soil management treatments. Left: Nontrafficked soil zone; Right: Trafficked soil zone. Darker line is the average and shadow is the standard deviation of the three repetitions. BD: bulk density; AC: aeration capacity; RFC: relative field capacity; PorM: macroporosity; PAWC: plant available water content.

Surprisingly, we found no significant impact of traffic on the yield. The results of the 2-way ANOVA suggest that soil tillage and vehicle traffic significantly impact all indicators at the 0.05 significance level (Supplementary Material, Table S3). However, multiple comparisons show that the difference is significant between MP and MT and DL and MT, but not between MP and DL (Supplementary Material, Table S4). We also found that the treatment significantly impacted the I_h indicator, but not the traffic. The I_h values are highest in the MT treatment, which is indicative of a higher homogeneity, that is, a lower volume of “loose soil pockets” as a result of compaction, a condition that is unfavorable to root development. I_h is lower in DL than in MP, which was expected as the soil preparation in DL is less intensive, resulting in a more

heterogeneous soil than in MP: DL’s soil profile is an aggregate of soil blocks spaced by voids filled with fine dirt (the “loose soil pockets”). For the I_h indicator, we found a significant effect of vehicle traffic at the $p = 0.06$ level for soils in MT but not in MP or DL.

4. Discussion

4.1. Generation of high-resolution profiles of soil variables and indicators of SPQ

We proposed a method for assessing the SPQ that integrates the tillage- and traffic-induced profile-scale soil structural heterogeneity. Our method uses a soil sampling strategy guided by the observations of the soil profile to cover the spatial heterogeneity in soil structure of each horizon. The soil sampling data are then combined with penetration resistance measurements at the profile scale. The latter measurements are characterized by a high spatial resolution and can be automated to a large extent. We found statistically significant relationships between the PR and BD and between BD and the soil hydrodynamic parameters $\theta_{v,s}$ (Eq. (1)) and K_s , which we used to generate high spatial resolution, 2D grids of the physical parameters of the soil’s Ap horizon. Although significant, our relationship between BD and K_s only explained 27% of the variability in the K_s values. This is because factors other than total porosity (BD) determine that parameter, starting with pore continuity that is partly missed due to the small size of the soil samples (Mallants et al., 1997). Despite these limitations, the relationship is significant and was deemed reliable to provide a valuable indication of the spatial variability and the range of that parameter. The lack of relationship between the curve-fitting parameter n in Eq. (1) and BD is consistent with previous studies showing that n is mainly a function of texture, not structure (Wösten et al., 2001). The resulting parameter grids allowed us to compute a set of SPQ indicators that integrate the soil profile heterogeneity otherwise missed in standard SPQ assessment procedures based on random soil sampling.

Our method is promising for assessing the effect of alternative soil management strategies on SPQ and tracking the long-term evolution of agricultural fields. The method can also be used to generate parameter grids for the parameterization of hydrodynamic models that capture the soil structural heterogeneity induced by tillage and vehicle traffic. Such structure is often omitted, although it is well established that it has a determining impact on the soil water and solute fluxes locally and at over larger scales (Fatichi et al., 2020). An important limitation of the method is that it is destructive and has to be conducted on bare soil, hence missing the immediate effect of crop roots on soil structure and making it inadequate for repeated measurements over a short period. Note that penetration resistance measurements are possible when the crop is in place for crops with a lighter root architecture which does not significantly influence the measurements, such as cereals. Geophysical methods could be used as alternative, non-destructive ways to characterize soil heterogeneity (Romero-Ruiz et al., 2018). However, even though such techniques allow revealing the soil structural units (e.g., Besson et al., 2004; Boizard and Richard, 2004; Jonard et al., 2013) or quantify soil moisture to some extent (e.g., Beff et al., 2013; Garré et al., 2011, 2013), no study to our knowledge has allowed deriving physical parameters and the common SPQ indicators as proposed here.

Some important considerations to keep in mind when using our method are the PR’s dependence on soil water content (Quraishi and Mouazen, 2013) and the impact of the soil properties in defining the type of PR-BD relationships. Consequently, different relationships may have to be established when the PR datasets are collected in profiles characterized by a broader range of soil texture or moisture conditions. In this study, we could ignore such effect since the different PR measurements were consistently taken at the beginning of the cropping season when the soils were expected to be at field capacity and hence with similar soil moisture content given the comparable soil textures of the surveyed agricultural fields. Moreover, any vertical gradient in soil

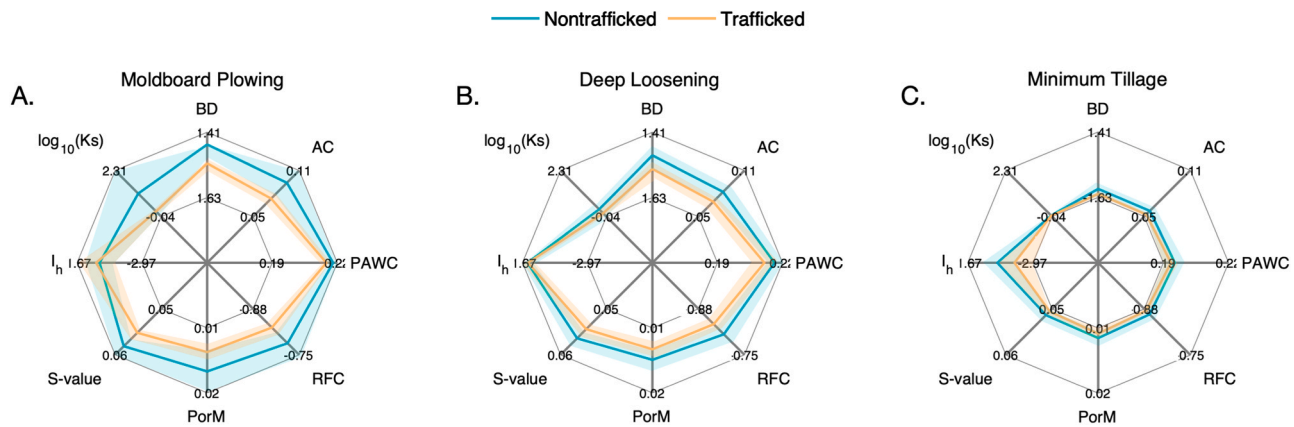


Fig. 10. Radar plots of the soil physical quality indicators for each soil management treatment. Darker line is the average value of the three repetitions averaged over compacted (green) or non-compacted (orange) spatial units, and clearer colors show the standard deviations of these three repetitions. Note that axes for BD, RFC and I_h are inverted. BD: bulk density; AC: aeration capacity; RFC: relative field capacity; PorM: macroporosity; PAWC: plant available water content; I_h : homogeneity index.

moisture or organic carbon was implicitly considered by establishing depth-dependent PR-BD relationships. The marker types and colors in Fig. 6 differentiate the soil texture, soil tillage type, and year of measurements in the data points used for the PR-BD relationship. The similar relationship regardless of the marker color or shape suggests the absence of any significant effect of these factors and validates the use of a unique relationship in this case study. However, these assumptions should be re-assessed whenever data from contrasting soil textures or tillage practices are used.

Among the indicator selected, the relevance of the S-value can be questioned given that it is highly dependent on the θ_r and n parameters whose values had been set to 0 and a constant, respectively. Despite this, we found the modelled retention curves – from which the S-value is derived – to fit tightly with the experimental data, including around the inflection point. This finding demonstrates the validity of using the indicator.

4.2. Assessment of the soil physical quality

When compared against ideal ranges and critical limits found in the literature, the indicators PAWC and S-value in Fig. 8 suggest that the study fields achieve good to very good physical quality. PAWC is always $> 0.2 \text{ cm}^3 \cdot \text{cm}^{-3}$ or within the $0.15\text{--}0.20 \text{ cm}^3 \cdot \text{cm}^{-3}$ range that is often considered optimal or good for root development and functioning (Hall et al., 1977; Reynolds et al., 2009; White, 2006). The S-value also indicates a good ($0.035\text{--}0.05$) to very good (≥ 0.05) physical quality value for all tillage practices (Dexter, 2004b; Dexter and Czyz, 2007; Tormena et al., 2008). Nevertheless, such a diagnostic does not hold when looking at the other indicators. For all treatments and traffick levels, BD is, for the most part, higher than the $0.9\text{--}1.3$ range, which is considered optimal for medium to fine-textured soils (Drewry, 2006; Reynolds et al., 2007). AC is below the threshold value for crop-damaging aeration deficit that some studies have set to $0.10 \text{ cm}^3 \cdot \text{cm}^{-3}$ (White, 2006) or even $0.14 \text{ cm}^3 \cdot \text{cm}^{-3}$ in sandy loam to clay loam soils (Carter, 1988; Mueller et al., 2009; White, 2006). RFC values are also greater than the ideal $0.6\text{--}0.7$ range that maximizes microbial production of nitrates. Finally, macroporosity is below the critical value of $0.04 \text{ cm}^3 \cdot \text{cm}^{-3}$, a value found in soils degraded by compaction (Carter, 1988; Drewry et al., 2001; Drewry and Paton, 2005). Such findings are particularly alarming as some have found macroporosity to be the best indicator of soil physical quality (Ball et al., 2007).

Another noteworthy aspect is that, although the suite of SPQ indicators scrutinized here was deemed adequate to test and exemplify the method, additional or alternative indicators of SPQ proposed in the literature could be considered and computed, such as those

discriminating between soil matrix and soil macropore domains (e.g., Reynolds et al., 2002) and the least limiting water range (LLWR, Kay, 1989; Letey, 1958). Additionally, the selected indicator values were compared to optimal values for agricultural crop support and development functions. However, soil functions or ecosystem services other than agricultural production, such as water flux regulation or filtering of pollutants, could be evaluated, in which case appropriate indicator sets and their ideal ranges or critical values should be determined (Andrews et al., 2004; Wienhold et al., 2009). A principal component analysis is a procedure commonly used as a data reduction technique to determine the minimum dataset to be integrated into a soil quality index (e.g., Andrews et al., 2002; Bünnemann et al., 2018; Chen et al., 2013; Gong et al., 2015; Liu et al., 2018; Zhao et al., 2017). Our method can help improve this process by allowing the computation of spatially integrated candidate indicators. The use of scoring functions that normalize indicator values from 0 (bad quality) to 1 (good quality) could facilitate the interpretation of indicator values and cross-comparison (Karlen et al., 1997).

Overall, we found the SPQ for the Ap soil horizon to be slightly higher in non-trafficked than trafficked soils and to be higher in MP than DL, and in DL than MT. This latter finding aligns with the lower yield of the sugar beets grown in MT and contrasts with a growing consensus on the advantages of MT in the scientific and agricultural community. However, our conclusions might differ if other soil types or soil functions had been assessed. Our results also have to be taken with caution given the relatively short time span over which the MT was applied (4 years) which might be too short for the benefits of using such technique to be fully developed. For example, the plots in MT could experience an enhanced structural quality due to the reduced number of tillage interventions and intensity of disturbances (Büchi et al., 2017). Such long-term treatment might also lead to improved quality as MT has repeatedly been found to be effective in increasing the soil organic content and enhancing the soil fertility (Büchi et al., 2017; de Cárcer et al., 2019; Maltas et al., 2013), or in improving the (micro-)biological activity (Mbuthia et al., 2015). Another limiting factor is that the assessment of SPQ was limited to the top 25 cm of the soil, hence omitting the evolution of the plow pan that might have resulted from a change in the soil preparation technique (Birkás et al., 2004) as well as indirect changes in soil structure below the tillage depth as a result of biological activity (Capowiez et al., 2009).

5. Conclusion

We proposed and tested a method to reconstruct profiles of soil physical parameters and indicators of SPQ at high spatial resolution,

capturing the tillage- and traffic-induced heterogeneity in soil structure. The method is based on penetration resistance (PR) measurements, soil core sampling, and standard laboratory analyses. For the studied loamy soils, we obtained robust relationships between field-measured bulk density (BD) and PR when taking depth as an adjustment parameter, between the parameters of van Genuchten's soil water retention function and BD, and to a lesser extent between Ks and BD. Hence, we succeeded in capturing the effect of soil structure on the former parameters. Using these relationships, we derived SPQ indicators that integrate the structural heterogeneity of the soil profile. As such, our method allows an assessment of the SPQ that is less dependent on the random sampling most commonly used in SPQ assessment procedures. Besides, it allows generating high-resolution grids of the van Genuchten equation's parameters that could further be used to parameterize hydrodynamic models. When applied to agricultural plots that underwent different soil tillage practices, our method allows highlighting and comparing the effects of vehicle traffic and tillage on the soil structure and the SPQ indicator values and variability.

Our method can be used to perform integrated assessments of SPQ in various agricultural fields, conduct a detailed characterization of the impact of alternative soil management practices on SPQ, and track the long-term temporal evolution of SPQ. Notably, such a method could also be useful for studying the impact of soil tillage and traffic-induced structural heterogeneity on soil hydrodynamics.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.still.2021.105236](https://doi.org/10.1016/j.still.2021.105236).

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