



**HAL**  
open science

## Relevance of a near infrared spectral index for assessing tillage and fertilization effects on soil water retention

Inès Soltani, Youssef Fouad, Didier Michot, P. Pichelin, Christophe Cudennec

### ► To cite this version:

Inès Soltani, Youssef Fouad, Didier Michot, P. Pichelin, Christophe Cudennec. Relevance of a near infrared spectral index for assessing tillage and fertilization effects on soil water retention. *Soil and Tillage Research*, 2019, 194 (104345), pp.12. 10.1016/j.still.2019.104345 . hal-02279488

**HAL Id: hal-02279488**

**<https://hal.science/hal-02279488>**

Submitted on 25 Oct 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# 1 **Relevance of a near infrared spectral index for** 2 **assessing tillage and fertilization effects on soil water** 3 **retention**

4

5 I. Soltani, Y. Fouad, D. Michot, P. Pichelin & C. Cudennec

6 UMR SAS, Agrocampus Ouest, INRA, 35000, Rennes, France

7

## 8 **ABSTRACT**

9 Agricultural practices are expected to have significant effects on soil physical properties, such  
10 as soil structure and soil water retention (SWR) properties are among the relevant properties  
11 that can be used to assess these effects. *Ex-situ* measurements are costly and time-consuming.  
12 Visible (vis) and near infrared (NIR) spectroscopy has been widely used as a rapid, cost-  
13 effective and nondestructive technique to predict many soil properties, including soil water  
14 content (SWC). In this study, we explored the ability of vis-NIR to assess the effects of soil  
15 tillage and fertilization on SWR. The study was performed on silty soil samples with 10.4 g  
16 kg<sup>-1</sup> of organic carbon content and a pH of 5-6.5. Undisturbed soil blocks were collected from  
17 an experimental station located in Brittany, France. In 2012, the field was designed as two  
18 separate experiments, each with a different tillage system (conventional tillage (CT) and  
19 shallow tillage (ST)). For each experiment, two fertilizer types were considered (mineral and  
20 organic). Six undisturbed soil blocks were sampled at each of two depths (0-15 cm and 15-25  
21 cm) and from each agricultural practice. Soil was sampled on two dates: before starting the

22 treatment (2012) and after 5 years of agricultural practices (2017). From each soil block, four  
23 aggregates 3-4 cm wide and 5-6 cm long were collected. The whole aggregates were set at a  
24 number of matric potentials, from saturation to the permanent wilting point ( $pF=4.2$ ). At a  
25 given pressure head, soil samples were scanned in triplicate to acquire reflectance spectra  
26 from 400-2500 nm using a handheld spectrometer (ASD Fieldspec®). We focused on the  
27 absorption band near 1920 nm and used a new NIR spectral index based on the band's full  
28 width at half maximum, called SWSI. Our results showed a linear relation between SWSI and  
29 SWC ( $R^2 > 0.99$ ). Moreover, the slope and intercept of this linear relation were significantly  
30 correlated with water holding capacity (WHC) and soil quality. Using these parameters, we  
31 found that SWR and soil physical quality under CT were significantly greater under cattle  
32 manure (CTC) than under mineral fertilizer (CTM) or at T0. This significant effect was more  
33 pronounced at 15-25 cm. In ST treatments, SWR properties and soil quality were significantly  
34 lower than at T0. More importantly, our results show that the slope and intercept of the linear  
35 relation offer a way to summarize and assess the effects of agricultural practices on SWR  
36 properties and soil structural quality.

37 **Keywords:** vis-NIR, NIR index, SWSI, soil water retention, soil physical quality, tillage,  
38 fertilization.

## 39 **1. Introduction**

40 Improved soil management techniques require identifying agricultural practices that are  
41 environmentally friendly and sustain crop yields. Therefore, there is growing interest in  
42 developing systems of shallow tillage (ST) as an alternative to conventional tillage (CT)  
43 (Roger-Estrade et al., 2010). CT systems have adverse effects on soil physical, chemical and  
44 biological properties and degrade soil ecosystems (IPBES, 2018). They may lead to the  
45 breakdown of organic matter, loss of soil moisture and change of water balance, the spread of  
46 salinity, increased susceptibility to wind and water erosion, and loss of soil biodiversity  
47 (Strudley et al., 2008). Conservation tillage systems, such as no-tillage (NT) and ST, can  
48 therefore help protect soil against compaction, erosion and degradation. ST and NT affect  
49 soil physical properties, such as bulk density (BD), soil water content (SWC), soil stability  
50 (Bottinelli et al., 2017; Czyż and Dexter, 2008; Lipiec et al., 2006; Strudley et al., 2008) and  
51 soil physical quality (Dexter, 2004b; Kabiri et al., 2015). However, concern has been  
52 expressed that NT crop production could lead to excess soil compaction. Excess compaction  
53 may decrease soil aeration and crop root development, thus restricting water uptake, nutrient  
54 availability and overall crop growth (Dalal et al., 1991; Lipiec and Nosalewicz, 2004;  
55 Mahmoodlu et al., 2016). Compaction can be assessed by BD measurements and soil water  
56 retention (SWR) properties.

57 For agricultural soils, fertilization is also a source of variability for SWR properties both in  
58 space and time (Bottinelli et al., 2017; Jiao et al., 2006; Mikha and Rice, 2004). Conventional  
59 soil management (i.e. intensive cultivation and the use of synthetic agrochemicals) has often  
60 been associated with degraded soil quality, whereas organic farming has been suggested as an  
61 approach to conserve and protect the soil environment (Abiven et al., 2009; Maillard and  
62 Angers, 2014). Several studies have investigated the differences between organically and  
63 conventionally managed soils (Bai et al., 2018; Maillard and Angers, 2014), but few have

64 sought to deal with potential differences in SWR properties and soil quality quantitatively in  
65 combination with tillage systems.

66 Accurate assessment of soil properties, traditionally using elemental analysis, is time-  
67 consuming and costly. Hence, sensor techniques are increasingly used to rapidly determine  
68 soil properties in the field (Minasny et al., 2014; Tauro et al., 2018). Among them, visible  
69 (vis) and near-infrared (NIR) spectroscopy have proven their potential to quickly estimate  
70 several soil properties, including particle-size distribution (Gomez et al., 2013; Janik et al.,  
71 2009), soil aggregate-size distribution (Cañasveras et al., 2010; Sarathjith et al., 2014), pH  
72 (Viscarra Rossel and Behrens, 2010), soil organic carbon (SOC) content (Nocita et al., 2013)  
73 and cation-exchange capacity (Soriano-Disla et al., 2014).

74 Rather than only estimating specific points of the SWR curve, recent studies developed  
75 transfer functions for soil hydraulic properties using spectral reflectance data. Using multiple  
76 linear regression between soil hydraulic properties and multiple attributes of measured  
77 spectral reflectance, Santra et al. (2009) defined transfer functions, called spectrotransfer  
78 functions (STFs). They used stepwise regression analysis and principal-component-  
79 transformed spectral data (350-2500 nm) as well as mimicked Landstat-ETM<sup>+</sup> spectral bands  
80 to estimate van Genuchten–Mualem (vGM) soil hydraulic parameters ( $\alpha$ ,  $n$ , and  $K_s$ ) of the wet  
81 part of the SWR curve (pressure head  $> -80$  kPa). Their results were promising for parameter  
82  $n$ , but they failed to estimate parameters  $\alpha$  and  $K_s$ . A major weakness of this approach is that  
83 the soil hydraulic parameters were estimated only from a small range of measured SWC.  
84 Other limitations include the use of disturbed soil samples, which usually lose some structural  
85 attributes, and the fact that they were collected from topsoil. Thus, the STFs may only be  
86 applicable to topsoils. Using spectral data as pedotransfer function (PTF) input provides an  
87 effective way of including temporal processes in hydrological models. Babaeian et al. (2015a,  
88 2015b) derived and validated the accuracy of STFs and spectral pedotransfer functions

89 (SPTFs) to predict the hydraulic parameters of the vGM SWR model. STFs relate hydraulic  
90 vGM parameters directly to spectral reflectance values, while SPTFs use additional basic soil  
91 data such as particle-size distribution and BD. The parametric STFs and SPTFs for the vGM  
92 model parameters were more accurate at low and intermediate water contents than PTFs,  
93 which were more accurate close to saturation. Both STFs and SPTFs estimated the SWR  
94 curve with accuracy similar to PTFs.

95 Recently, Soltani et al. (2019) evaluated the potential of NIR spectroscopy to estimate SWC.  
96 They defined a spectral index called the “soil water spectral index” (SWSI), based on the full  
97 width at half maximum of the absorption band near 1920 nm. They showed that the SWSI  
98 decreases linearly with an increase in SWC. Moreover, they found that the parameters of this  
99 linear relation were correlated with soil texture and SOC content. Furthermore, their results  
100 indicate that SWSI can be useful for studying how texture and SOC content affect SWR  
101 properties, water holding capacity (WHC) and therefore soil structure.

102 Based on Soltani et al.’s (2019) results, we examined the effectiveness and robustness of the  
103 SWSI in estimating medium-term (five year) impacts of CT and ST, combined with two  
104 fertilizer inputs, on SWR properties. We present a comparative analysis of spectral  
105 information and soil property data to assess tillage and fertilization impacts on SWR  
106 properties and soil physical quality.

## 107 **2. Materials and methods**

### 108 *2.1. Experimental site and tillage systems*

109 The study was performed at the EFELE (*EFfluentes d’ELevage et Environnement*)  
110 experimental site in Le Rheu, in western France (48°05’34.94” N, 1°48’54.27” W). This field  
111 experiment is part of the French “Organic Residues” research observatory (SOERE PRO),  
112 which is a network of long-term field experiments on the impacts of organic residue

113 application in agriculture (more information on SOERE PRO and EFELE is available at  
114 [www6.inra.fr/valor-pro\\_eng/Experimental-devices/EFELE](http://www6.inra.fr/valor-pro_eng/Experimental-devices/EFELE)). The EFELE site, established in  
115 2012, assesses the agronomic value of composts and the environmental impacts of organic  
116 waste from livestock production. EFELE's soils are silty loam, classified as Epistagnic Haplic  
117 Luvisols according to the World Reference Base for Soil Resources (IUSS Working Group  
118 WRB, 2014), with a pH of 6.1, a SOC content of 10.4 g kg<sup>-1</sup> and particle-size distribution of  
119 143 g kg<sup>-1</sup> clay, 705 g kg<sup>-1</sup> silt and 153 g kg<sup>-1</sup> sand in the upper 30 cm.

120 The experimental design consisted of two separate experiments, each with a different tillage  
121 system, CT and ST. For each trial, two fertilizer treatments (mineral and organic) were  
122 considered and randomly replicated three times (Figure 1). Therefore, the experimental  
123 system was composed of a total of 12 plots (12.5 m × 8.7 m). The crop rotation was maize  
124 (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.), with a nitrogen (N) catch crop of  
125 mustard (*Sinapis hirta*) between wheat and maize.

126 The four treatments studied were i) CT with mineral fertilizer (CTM), ii) CT with cattle  
127 manure (CTC), iii) ST with mineral fertilizer (STM) and iv) ST with cattle manure (STC).  
128 The CT was deep plowing to a depth of 22 cm with a moldboard and circular spike, while the  
129 ST was performed with a "Compil" equipped with circular rolling spades to a depth less than  
130 10 cm, without soil inversion. The mineral fertilizer was N applied as ammonium nitrate, with  
131 a mean dose of 92 kg N/ha on maize and 118 kg N/ha on wheat. This dose was calculated by  
132 considering crop needs, soil mineralization rate and an annual input of 50 kg of P<sub>2</sub>O<sub>5</sub>/ha and  
133 60 kg of K<sub>2</sub>O. The organic fertilizer (cattle manure) was applied before seeding the maize,  
134 using a spreader at a mean dose of 50 t/ha every two years beginning in 2012, and then  
135 landfilled using a "Compil" at a depth of 6 to 8 cm. The dose was calculated based on an  
136 annual input of 100 kg of P<sub>2</sub>O<sub>5</sub>/ha. The cattle manure provided more than 4 t/ha of organic  
137 matter per year.

138 Two undisturbed soil blocks were collected at each plot: one each at 0-15 and 15-25 cm. Each  
139 plot's soil was sampled twice: in February 2012, to define the initial state (T0) before starting  
140 treatments, and in March 2017, after five years of treatments. The two sampling campaigns  
141 were conducted before tillage. After each sampling campaign, the 24 soil blocks collected  
142 were stored at 4°C until required for physical and spectral measurements.

## 143 2. 2. *Assessment of the effects of agricultural practices on soil hydraulic properties*

### 144 2. 2. 1. Conventional approach based on soil physical and chemical properties

145 In the laboratory, each soil block was broken down at field capacity into aggregates  
146 approximately 3-4 cm wide and 5-6 cm long. Four aggregates were collected in quadruplicate  
147 for measurement. Once saturated with deionized water, all aggregates were placed on a  
148 suction table and then in a pressure cell to be gradually dried. Aggregates were brought  
149 successively to pressure heads of -1 and -3.2 kPa (corresponding to pF 1 and 1.5,  
150 respectively) on the suction table. Then they were brought to pressure heads of -10, -20, -  
151 31.6, -63, -100, -316, -1000 and -1585 kPa (corresponding to pF 2, 2.3, 2.5, 2.8, 3, 3.5, 4  
152 and 4.2, respectively) using a pressure cell following the ISO 11274 standard (AFNOR,  
153 1998). At each pressure head, the soil aggregates were weighed. Finally, the aggregates were  
154 oven-dried at 105°C for 48 hours, after which their dry mass was weighed to determine their  
155 gravimetric SWCs at the matric potentials. Dry BD was measured for whole aggregates by the  
156 kerosene-displacement method (Abrol and Palta, 1968), according to the X31-505 standard  
157 (AFNOR, 1992). For each soil aggregate, gravimetric SWC was converted to volumetric  
158 SWC, and total porosity was calculated assuming a particle density of 2.65 g cm<sup>-3</sup>. The SWCs  
159 of the four aggregates were averaged at different pressure heads, and their BDs were averaged  
160 after they had been oven-dried. Their BDs were measured following kerosene displacement.  
161 WHC for a specific thickness, z (cm), of soil was calculated as follows:

162  $WHC = (SWC_{FC} - SWC_{PWP})BD z$  (1)

163 where FC is field capacity and PWP is permanent wilting point. Furthermore, when FC was  
 164 not measured in the field, it was often estimated to be SWC around a pressure head of -33  
 165 kPa, particularly for loamy soil (Kirkham, 2014). For our soil samples, we used the pressure  
 166 head of -31.6 kPa (i.e. pF=2.5) to assess SWC at FC. WHC was calculated for a standard  
 167 thickness  $z$  of 10 cm. Based on SWR characteristics, we estimated pore-size distribution  
 168 according to capillary theory (Ahuja et al., 1998), assuming that pores were cylindrical  
 169 capillaries described by Jurin's equation:

170  $S = \frac{2\gamma\cos\beta}{\rho gr}$  (2)

171 where  $S$  (m) is soil water suction ( $S = -h$ , the pressure head),  $r$  is the effective pore radius,  $\gamma$  is  
 172 the surface tension of water (at 20°C,  $\gamma=0.075 \text{ N m}^{-1}$ ),  $\beta$  is the contact angle of the water held  
 173 in the pore (usually assumed to be zero,  $\cos\beta = 1$ ),  $\rho$  is the density of water ( $1000 \text{ kg m}^{-3}$  at  
 174 20°C), and  $g$  is gravitational acceleration ( $9.81 \text{ N kg}^{-1}$ ).

175 The diameter  $d$  ( $\mu\text{m}$ ) of the largest pores was calculated with a simplified equation:

176  $d = \frac{0.3}{S}$  (3)

177 It is well known that the impacts of soil tillage and fertilization are directly related to major  
 178 physical and chemical soil properties such as SWC, WHC, BD, porosity and SOC content.  
 179 Thus, in the conventional approach, the effects of tillage type and fertilizer type on these  
 180 properties were examined to infer their effects on SWR properties. Additionally, impacts on  
 181 soil structure and quality were estimated with the  $S_{Dexter}$  index of soil physical quality (Dexter,  
 182 2004a):

183  $S_{Dexter} = -n(SWC_0 - SWC_r) \left[1 + \frac{1}{m}\right]^{-(1+m)}$  (4)

184 where  $SWC_0$  ( $\text{cm}^3 \text{ cm}^{-3}$ ) is SWC at saturation,  $SWC_r$  ( $\text{cm}^3 \text{ cm}^{-3}$ ) is the residual soil water  
185 content,  $n > 1$  is a measure of the pore-size distribution and  $m$  is an empirical constant that  
186 can be related to  $n$ , such that  $m = 1 - 1/n$  (Van Genuchten, 1980). During the adjustment  
187 process,  $SWC_r$  was found to be close to zero. It was therefore set to zero for all samples. In  
188 fact,  $S_{\text{Dexter}}$  equals the slope of the SWR curve at its inflection point (Dexter, 2004a). Dexter  
189 (2004b) showed that  $S_{\text{Dexter}}$  is linearly and positively correlated with friability and the ease of  
190 working the soil. Thus, as  $S_{\text{Dexter}}$  increases, soil compaction decreases, which indicates good  
191 soil structure.

#### 192 2. 2. 2. Alternative approach with spectral measurements

193 Once the desired water pressure head was reached, and after the soil aggregates had been  
194 oven dried, reflectance spectra of soil samples were recorded with a full-range visible–NIR  
195 spectrometer (ASD Fieldspec® 3, Analytical Spectral Devices Inc., Boulder, CO, USA) from  
196 350-2500 nm wavelengths, with a sampling interval of 1 nm. The ASD spectrometer was used  
197 in a bare fiber optic configuration with a  $25^\circ$  view angle. All spectra were recorded using a  
198 standard contact probe that embeds both an optical fiber and a halogen bulb light source with  
199 a color temperature of approximately 2901 K. This reduces errors associated with stray light  
200 during measurement and atmospheric water content. Before spectral acquisition of each soil  
201 sample, the ASD spectrometer was optimized on a dark current followed by a white reference  
202 panel (Spectralon®). Spectral measurements were taken in the laboratory in a dark room. At a  
203 given pressure head and for each soil aggregate, reflectance spectra were acquired in triplicate  
204 by slightly modifying the position of the contact probe. As a result, the single spectrum for a  
205 given soil aggregate at a given moisture was a mean of 30 scans, and the final spectrum used  
206 in the treatment was a mean of the three replicates. The total time for recording the spectra  
207 was standardized to 6 s per aggregate to avoid heating and drying the samples. Because of the  
208 low signal-to-noise ratio between 350 and 400 nm, the spectral interval was narrowed to 400-

209 2500 nm (Mouazen et al., 2010), and the continuum removal technique (Clark and Roush,  
210 1984) was applied to all spectral data. It was applied to facilitate the interpretation of the  
211 absorption features in a diffuse reflectance spectrum by normalizing spectra to a common  
212 convex hull.

213 In this alternative approach, the spectral reflectance values, and more precisely the SWSI,  
214 referred to in Soltani et al. (2019), were used as a unique predictor of the impacts of soil  
215 tillage and fertilization on SWR properties:

$$216 \quad SWSI_i = 1 - \frac{FWHM_i}{FWHM_0} \quad (5)$$

217 where  $i$  is a value of pressure head,  $FWHM_i$  is the full width at half maximum at the  $i$ th  
218 pressure head and  $FWHM_0$  is the full width at half maximum at saturation.

219 Thus, using spectral data, we calculated the  $SWSI_i$  at the 11 available matric potentials: 0, -1,  
220 -3.2, -10, -20, -31.6, -63, -100, -316, -1000 and -1585 kPa. As in Soltani et al. (2019), the  
221 linear relation between SWSI and SWC was fitted for each soil sample to obtain the slope (i.e.  
222 the rate of water release from soil pores) and intercept (i.e. SWC at saturation). Thus, as the  
223 intercept increases, the maximum WHC of the soil increases, and as the absolute value of the  
224 slope (AvS) increases, SWR decreases. We also used the projection and position of soil  
225 samples on the slope vs. intercept plane to study the impact of tillage and fertilization on soil  
226 structure and SWR properties.

### 227 2. 3. *Statistical analysis*

228 The experimental design consisted of two separate trials, each with a different tillage type (CT  
229 or ST), with two fertilizer treatments (mineral and organic) randomly replicated three times  
230 within each trial. Therefore, statistical analyses were carried out separately for the two trials.  
231 All statistical analyses were performed using the R statistical programming environment (v.

232 3.5.0). Descriptive statistics of basic soil properties and soil spectral data were calculated and  
233 tested for normality (at  $P < 0.05$ ) using the Shapiro–Wilk test statistic. Analysis of variance  
234 (ANOVA) was used for both tillage systems to determine whether the effects of fertilizer type  
235 and soil depth and their interactions on soil physical and chemical properties and spectral data  
236 were significant. Prior to ANOVAs, the data were tested for homoscedasticity using Bartlett’s  
237 test. When effects were significant at  $P < 0.05$ , means were compared with Fisher’s least  
238 significant difference (LSD) test. Pearson’s correlation analyses were also performed to  
239 explore correlations between soil properties (WHC, BD, sand:clay ratio and  $S_{\text{Dexter}}$ ) and  
240 spectral parameter data (intercept and slope).

### 241 **3. Results**

#### 242 *3.1. Soil organic carbon content and bulk density*

243 ANOVA showed that for ST soil fertilization, depth and their interaction had a significant  
244 effect at  $P < 0.05$  on SOC content (Table 1). In contrast, for CT, the significant effects at  
245  $P < 0.05$  were only observed for depth on SOC and for soil fertilization on BD.

246 Pairwise comparison of mean BD and SOC content between soil depths at T0 and under each  
247 CT treatment (CTM and CTC) showed no significant difference except for T0, where SOC  
248 content was significantly higher at 0-15 cm (Table 2). Moreover, the mean BD and SOC did  
249 not differ significantly between T0, CTM and CTC, regardless of depth. In the case of the ST  
250 treatment, the comparison of mean BD did not show any significant difference between soil  
251 depths for a given treatment or between T0, STM and STC at each depth. In contrast, at 0-15  
252 cm cattle manure fertilization had significantly higher SOC than at T0 or with mineral  
253 fertilization. Cattle manure’s positive effect on SOC content was much more noticeable at 0-  
254 15 cm, for which cattle manure fertilization had a SOC content 20% higher than at T0 and  
255 10% higher than for mineral fertilization. At 15-25 cm, the mean SOC of STM and STC was

256 significantly lower than at T0. The comparison of mean SOC between soil depths showed a  
257 significant difference for STM and STC, but not for T0 (Table 2). Thus, under cattle manure  
258 (STC) and mineral fertilizer (STM), SOC content at 15-25 cm was 20% lower than at 0-15  
259 cm.

260 Although five years of CT had no significant effect on SOC content, regardless of fertilizer  
261 treatment or depth, CTC had a slightly higher SOC content than at T0 or under CTM (Table  
262 2). On the other hand, ST combined with mineral or organic input showed a significant  
263 increase in SOC content at 0-15 cm compared to T0, unlike in the untilled layer at 15-25 cm,  
264 where it significantly decreased. Furthermore, five years of both CT and ST did not show any  
265 significant difference when comparing BD to T0, regardless of soil depth or fertilizer input  
266 (Table 2). However, according to the ANOVA (Table 1), fertilizer inputs had a significant  
267 effect under CT, and BDs were slightly higher (Table 1) under tilled layers with mineral or  
268 organic input than at T0.

### 269 3. 2. *Soil water retention characteristics*

270 After five years of CT and ST treatments in combination with mineral and organic fertilizer  
271 inputs, the mean SWC, at pressure heads of  $-3.2$  kPa and  $-31.6$  kPa, did not differ  
272 significantly from T0 at 0-15 cm (Table 3). In contrast, at a pressure head of  $-1585$  kPa, the  
273 mean SWC showed a significant difference between T0 and CTM, and between STM and  
274 STC. SWC under CTM was 7% greater than at T0, and 10% greater under STC than STM.  
275 For soil layers at 15-25 cm, the only significant difference was observed between SWR under  
276 CTC and both T0 and CTM, at pressure heads of  $-3.2$  kPa and  $-31.6$  kPa. SWR under CTC  
277 was 9% and 6% greater at T0 and under CTM, respectively. In the case of ST treatments,  
278 SWC differed significantly only between STM and STC at a pressure head of  $-1585$  kPa, and  
279 it was 11% lower under mineral than under cattle manure fertilization. WHC showed a

280 significant effect of tillage and fertilizer input combinations only at 15-25 cm. WHCs were  
281 highest under CT, but differed significantly only between CTC and T0, where WHC under  
282 CTC was 20% higher than at T0. Among the T0, STM and STC untilled layers, a significant  
283 difference was obtained between STM and STC, and WHC with mineral input was 10%  
284 higher than with organic input.

285 Figure 2 shows the difference in SWC between the treatments and T0 as a function of  
286 pressure head, at 0-15 cm and 15-25 cm. To a certain extent, the observed variations among  
287 treatments reflect differences in poral distribution between each treatment and T0. One can  
288 see that CT and ST combined with the fertilizer inputs did not behave similarly. Indeed, the  
289 difference in SWC for CT under cattle manure was positive over the entire pressure head  
290 range at both soil depths, and it was greater than or equal to the difference under mineral  
291 fertilization for pressure heads higher than  $-1585$  kPa. Overall, SWC under CT was higher  
292 than at T0, and the increase was more pronounced with cattle manure than with mineral input.  
293 The difference in SWC between CTM and T0 was positive except at some pressure heads in  
294 the interval  $[-1000$  kPa,  $-10$  kPa], where it was slightly negative. At the permanent wilting  
295 point ( $-1585$  kPa), the difference in SWC under CTM was higher than under CTC. Overall,  
296 the difference in SWC under STC and STM relative to T0, as a function of pressure head, had  
297 similar variations at both depths (Figure 2). Moreover, this difference was negative mainly in  
298 the pressure head interval  $[-316$  kPa,  $-10$  kPa], regardless of depth and fertilizer type. Unlike  
299 under CT, the effect of cattle manure under ST did not lead to increased SWC compared to T0  
300 and even to STM. Thus, the difference in SWC with STC was lower than or equal to that with  
301 STM, everywhere except at the permanent wilting point (Figure 2).

302 3.3. *Pore-size distribution*

303 For both experimental trials (CT and ST), fertilization and depth greatly modified the pore-  
304 size distribution (Figure 3). Macropore (diameter > 100  $\mu\text{m}$ ) volume was significantly larger  
305 under ST and CT than at T0 at both depths in the two trials. Mesopore (30-100  $\mu\text{m}$ ) volume  
306 did not differ significantly among treatments in both trials except under STM, which had  
307 significantly larger mesopore volume than at T0 or under STC, regardless of depth. Small  
308 pores (0.2-30  $\mu\text{m}$ , “storage micropores”) occupied the majority (ca. 50%) of pore volume, and  
309 their volume did not differ significantly among treatments in both trials. Only CTC showed a  
310 significant increase in storage micropore volumes compared to T0 and CTM at 15-25 cm. In  
311 the CT trial, the volume of very small pores (< 0.2  $\mu\text{m}$ , “residual micropores”) was  
312 significantly larger under CTM than at T0 or under CTC at 0-15 cm, while at 15-25 cm there  
313 was no significant difference between treatments. Under ST, the volume of residual  
314 micropores was significantly smaller under STM than at T0 or under STC, regardless of  
315 depth.

316 3.4. *Soil structure and soil quality*

317 Soil fertilization showed a significant ( $P < 0.05$ ) difference in the  $S_{\text{Dexter}}$  soil physical quality  
318 index, compared to T0 in the CT experimental trial or in the ST trial. In the CT experimental  
319 trial, CTC and CTM had significantly smaller values of  $S_{\text{Dexter}}$  (i.e. poor soil structure) than  
320 T0 at 0-15 cm, while no difference was observed at 15-25 cm (Figure 4). At both depths,  
321 STM had significantly lower  $S_{\text{Dexter}}$  than T0, but the STC treatment had a significant effect  
322 only at 15-25 cm with an  $S_{\text{Dexter}}$  index lower than that at T0. In addition,  $S_{\text{Dexter}}$  values under  
323 STC varied widely at 0-15 cm (Figure 4).

324 3. 5. *Using the SWSI to assess soil tillage and fertilizer impacts*

325 When we examined the relation between SWC and SWSI for all soil samples, measured SWC  
326 showed a highly significant ( $P \ll 10^{-8}$ ) linear relation with the SWSI ( $R^2 > 0.98$ , Table 4),  
327 decreasing as the SWSI increased (Figure 5), regardless of depth or fertilizer input. These  
328 results agree with Soltani et al. (2019), who found a decreasing linear relation between SWC  
329 and SWSI. The slopes of the regression lines ranged from  $-1.27$  (CTM at 0-15 cm and CTC at  
330 15-25 cm) to  $-1.16$  (STC at 0-15 cm). In the subsequent analysis, we examined the absolute  
331 value of the slope (AvS).

332 The slope and intercept of the linear relation between SWC and SWSI were mainly influenced  
333 by soil tillage and fertilization (Figure 5, Table 4). At 0-15 cm, STM had the largest intercept  
334 ( $0.509 \text{ cm}^3 \text{ cm}^{-3}$ ), while T0 had the smallest ( $0.476 \text{ cm}^3 \text{ cm}^{-3}$ ) (Table 4). At the same depth,  
335 CTM had the largest AvS (1.27), while STC had the smallest (1.16). At 15-25 cm, CTC had  
336 the largest intercept and AvS ( $0.528 \text{ cm}^3 \text{ cm}^{-3}$  and 1.27, respectively), while T0 had the  
337 smallest intercept ( $0.491 \text{ cm}^3 \text{ cm}^{-3}$ ) and STC the smallest AvS (1.20). ANOVA of the  
338 intercept and AvS (Table 5) indicated that under the CT treatment, depth and fertilization had  
339 a significant effect only on the intercept at  $P < 0.05$ , and no interaction was found between  
340 these two factors (depth and fertilization). In the case of the ST treatment, these factors had no  
341 significant effect on the intercept or on the AvS.

342 When we graphed the mean AvS vs. the mean intercept at T0 and under the four treatments  
343 (Figure 6), their distribution on the plane was related to soil tillage, fertilization and depth.  
344 Therefore, the relative position of a given soil treatment on this plane allows to compare its  
345 two properties, SWR and maximum WHC, with respect to those of the other treatments.  
346 Indeed, increasing the intercept leads to an increase in maximum WHC, while increasing the  
347 AvS leads to a decrease in SWR. The mean intercept and the mean AvS ranged from  $0.476$ -  
348  $0.528 \text{ cm}^3 \text{ cm}^{-3}$  and  $1.20$ - $1.27$ , respectively, under CT (Figure 6a), while under ST, they

349 ranged from 0.490-0.509 cm<sup>3</sup> cm<sup>-3</sup> and 1.16-1.23, respectively (Figure 6b). In addition, CTM  
350 at 0-15 cm and CTC at 15-25 cm had a larger AvS than T0 and ST, regardless of depth and  
351 fertilization.

352 At 0-15 cm, moving from T0 to CTC mainly increased the mean intercept, while moving to  
353 CTM increased both the mean AvS and the mean intercept. Consequently, CTC had higher  
354 maximum WHC than that at T0, and CTM had higher maximum WHC and lower SWR  
355 compared to T0. Moving from T0 to STC or STM, the mean AvS decreased and thus SWR  
356 increased. However, STM had a higher intercept, and thus higher maximum WHC, than at T0.  
357 At 15-25 cm, both the mean intercept and the mean AvS linearly increased when moving  
358 from T0 to CTM and then to CTC. On the other hand, STM had a higher mean intercept and  
359 mean AvS than that STC or at T0. Consequently, STM had a higher maximum WHC than at  
360 T0 at both depths.

### 361 3. 6. *Correlation between soil physical properties and the AvS and intercept*

362 Pearson correlations between the AvS, intercept and soil physical and chemical properties  
363 (BD, WHC, SOC content and S<sub>Dexter</sub>) (Table 6) generally agreed with the previous results. The  
364 AvS was positively and significantly correlated with WHC ( $r = 0.62$ ) and S<sub>Dexter</sub> ( $r = 0.39$ ), but  
365 not with BD or SOC content. The intercept was also positively and significantly correlated  
366 with WHC ( $r = 0.64$ ) and S<sub>Dexter</sub> ( $r = 0.34$ ) and negatively (but not significantly) correlated  
367 with BD ( $r = -0.18$ ). Besides the correlation with the intercept and the AvS, S<sub>Dexter</sub> was also  
368 positively and significantly correlated to SOC ( $r = 0.21$ ) and WHC ( $r = 0.74$ ), while it was  
369 negatively and significantly correlated to BD ( $-0.25$ ).

## 370 **4. Discussion**

### 371 *4.1. Impacts on soil organic carbon content*

372 The effects of soil tillage and fertilization on soil properties vary, and these variations depend  
373 on the system chosen. Many studies have compared the influence of CT and ST on soil  
374 physical, chemical and biological properties, often reporting contradictory results (Alvarez  
375 and Steinbach, 2009; Balesdent et al., 2000; Kabiri et al., 2015). The effects of tillage and  
376 fertilization on SOC content dynamics have long been studied because of their impacts on soil  
377 quality and functioning. As expected, organic fertilization immediately increases SOC  
378 content, generally in proportion to the amount of carbon applied (Larney and Angers, 2012).  
379 Our results showed significantly higher SOC content after five years of cattle manure  
380 fertilization than with mineral fertilization. Besides fertilization, SOC content was higher  
381 under ST than under CT. In this case, the positive effect of ST on SOC content was observed  
382 only at 0-15 cm, and CT had higher SOC contents at 15-25 cm than ST. In ST soils, crop  
383 residues and cattle manure enter and decompose in the topsoil. Thus, SOC content at 0-15 cm  
384 is generally higher under ST than under CT. The fresh organic matter that is lost during tillage  
385 and decomposes at depth can also explain the high SOC content under CT at 15-25 cm. Many  
386 studies tend to show considerably higher rates of carbon mineralization in the topsoil under  
387 ST or NT than under CT (Bescansa et al., 2006; Green et al., 2007). Our results suggest that  
388 five years of CT and cattle manure input increase SOC contents at 15-25 cm.

### 389 *4.2. Impacts on bulk density*

390 Reviews of how tillage systems influence BD have yielded contradictory results. Some  
391 studies found that BD increased under NT compared to CT or ST (Alvarez and Steinbach,  
392 2009; Bescansa et al., 2006; Osunbitan et al., 2005; Salem et al., 2015). Conversely, other  
393 reviews found that tillage systems had inconsistent effects on BD and total porosity (Kabiri et

394 al., 2015; Strudley et al., 2008). In the present study, BD at 0-15 cm was higher under both ST  
395 and CT than at T0, which agrees with Strudley et al.'s (2008) results. BD was also slightly  
396 higher under CT than under ST, perhaps due to the longer persistence of loosened soil after  
397 chiseling than after moldboard plowing (Richard et al., 2004). The decrease in BD after ST  
398 agrees with the results obtained by Green et al. (2003), Moret and Arrúe (2007) and Strudley  
399 et al. (2008), among others. However, BD decreased only at 0-15 cm, with no significant  
400 difference between ST and CT at 15-25 cm, which is similar to Ferreras et al.'s (2000)  
401 findings. These results suggest that soils under CT were denser, most likely due to subsequent  
402 compaction in the topsoil. Plant root development may have increased soil porosity and  
403 consequently decreased BD under ST, since ST could favor more root development in the  
404 topsoil. Indeed, increased soil porosity due to increased SOC content at 15-25 cm in tilled  
405 soils may explain the lower BD in the study plots.

#### 406 4. 3. *Impacts on pore-size distribution*

407 Soil porosity is a key characteristic controlling SWR properties and plant root development,  
408 but it is also an important indicator of soil physical quality as influenced by agricultural  
409 practices. Tillage generally affects structural porosity, which results from the arrangement of  
410 soil aggregates, but not textural porosity, which is determined mainly by soil texture (Guérif  
411 et al., 2001). In the present study, soil porosity was lower under both CT and ST than at T0,  
412 but no significant difference was observed either at 0-15 cm or at 15-25 cm. The decrease in  
413 soil porosity, especially structural, was due mainly to the decrease in soil volume during  
414 compaction, due in part to tractor use. Pore size distribution describes the complexity of  
415 structure in far more detail than porosity alone. For example, it is the fundamental basis for  
416 the concept of aggregates. Pore size can be classified into micropores, macropores, and in  
417 some definitions, mesopores. In the present study, agricultural practices showed differences in  
418 soil behavior due to water and air movement. The percentage of macropores was significantly

419 higher under CT and ST treatments than at T0, with no significant difference in the  
420 percentage between organic and mineral fertilizers. Macropores play a major role in water  
421 movement and also serve as channels for root development and solute movement (Jarvis,  
422 2007). Differences in macropore distribution between tilled soil (CT and ST) and T0 were  
423 most likely the result of less soil disturbance at T0. CT generally disrupts macroaggregates  
424 mechanically (Kabiri et al., 2015). Our findings agree with the results of Ferreras et al. (2000)  
425 and Bescansa et al. (2006). Other studies have also reported fewer macropores under CT than  
426 under conservation tillage (Osunbitan et al., 2005). Mesopore distribution did not differ  
427 significantly among treatments in both CT and ST trials. Only STM had a greater mesopore  
428 volume than STC and T0. The pore-size distribution also indicated no significant difference in  
429 the percentage of storage micropores among CT and ST treatments compared to T0. Only  
430 CTC had greater storage micropore volume at 15-25 cm. Overall, tillage (CT and ST) in  
431 combination with fertilizer input appeared to appreciably change the volume of i) macro and  
432 mesopores at both depths, ii) storage micropores at 15-25 cm and iii) residual micropores at 0-  
433 15 cm. The results of pore-size distribution agree with the behavior of BD and tillage-induced  
434 pores. Pore-size distribution is also modified by fertilization. The complex chemical and  
435 physical characteristics of fertilizers have variable effects on aggregation. Fertilizer  
436 applications generally increase soil aggregation and can increase both macroporosity and  
437 microporosity. This probably explains the increase in micropore volume at 15-25 cm under  
438 CTC.

#### 439 4. 4. *Impacts on soil water retention properties*

440 The relation between pore-size distribution and SWR properties among soil tillage systems  
441 and fertilization is complex. Water is held in the spaces (pores) between soil particles and  
442 within films surrounding these particles. SOC content and particle-size distribution affect a  
443 soil's ability to retain moisture and its WHC. The sum of the adsorbed and retained SWC is

444 equal to the saturated SWC (Liu et al., 2013). Many factors can influence WHC, and the  
445 response to tillage may be uncertain (Strudley et al., 2008). Azooz and Arshad (2001)  
446 measured SWR at six matric suctions from 5-160 kPa and found that the rate of soil drying at  
447 0-30 cm was significantly higher under CT than NT, while the rate of wetting was  
448 significantly higher under NT. In the present study, SWR characteristics, particularly WHC,  
449 were greater under CT than at T0. The differences in SWR observed between treatments  
450 resulted from a change in the pore-size distribution for compaction in a range of sizes  
451 corresponding to pores that contribute to SWR. Our results showed that tillage and  
452 fertilization affect SWR properties for pressure heads ranging from -1 to -1585 kPa. The  
453 increase in retained SWC from -1 to -31.6 kPa probably corresponds to an increase in macro-  
454 and mesopore volume. In the same way, the increase in retained SWC from -31.6 to -1582  
455 kPa would correspond to the increase in storage micropore volume. The presence of small  
456 pores could have favored higher SWC, and under CT, cattle manure fertilization helped  
457 maintain higher SWC at 15-25 cm.

#### 458 4. 5. *Impacts on soil structure quality*

459 Soil physical quality, as indicated by  $S_{Dexter}$ , was adequate for the soil and layers studied.  
460 Regardless of the treatment, mean  $S_{Dexter}$  was above the critical value (0.035) proposed by  
461 Dexter (2004a), indicating good soil structural and physical quality. Even after the repeated  
462 traffic over a five year period in both the ST and CT experimental trials, the soil maintained  
463 good structure. In addition,  $S_{Dexter}$  tended to increase in organic fertilizer treatments, but not  
464 with mineral fertilization. Overall, compared to T0, physical soil quality in both CT and ST  
465 trials decreased, except for an improving trend at 15-25 cm with cattle manure input under  
466 CT. It is likely that spreading cattle manure increased SOC content and improved soil  
467 structure. SOC content is an important indicator of soil quality because of its significant  
468 effects on soil physical, chemical and biological properties. SOC is closely related to soil

469 aggregate formation and stabilization (Balesdent et al., 2000). It is also strongly affected by  
470 agricultural management practices such as tillage (Six et al., 2002). In general, increasing  
471 SOC content can generally improve aggregate stability, suggesting that organic fertilization  
472 promotes greater structural stability and subsequently an improvement in soil structural  
473 quality.

474 According to Dexter (2004a),  $S_{Dexter}$  generally decreases with increasing BD. This agrees with  
475 the data shown here, in which the lowest  $S_{Dexter}$  values coincided with the highest BDs. The  
476 relation between  $S_{Dexter}$  and BD, however, depends on soil texture (Dexter, 2004a). Recently,  
477 Naderi-Boldaji and Keller (2016) found a positive correlation between soil compaction and  
478  $\ln(1/S_{Dexter})$  that is less sensitive to soil texture.  $S_{Dexter}$  was generally lower under CT and ST  
479 than at the initial state. The compaction of soil due to tractor use in CT and ST could explain  
480 the decrease in  $S_{Dexter}$  and thus soil physical quality.  $S_{Dexter}$  is derived from the SWR curve.  
481 Therefore, it is closely related to pore-size distribution, which agrees with the variations in  
482 pore-size distribution observed among the treatments.

#### 483 4. 6. *Utility of the SWSI for evaluating soil tillage impacts on SWR properties*

484 In addition to the effects observed on SWR properties and soil quality, we considered the  
485 effect of tillage and fertilization on soil NIR reflectance. We were particularly interested in  
486 the SWSI NIR spectral index developed by Soltani et al. (2019) and the parameters of the  
487 SWC-SWSI relation. SWSI showed a significant linear relation with measured SWC, with an  
488  $R^2 > 0.99$  for all soil samples, which agrees with Soltani et al.'s (2019) results. They obtained  
489 a similar linear relation between SWC and SWSI from several soil samples taken from the  
490 organo-mineral A horizon (0-30 cm) in Brittany. SWC decreases linearly as SWSI increases.  
491 As suggested by Soltani et al. (2019), the AvS indicates how much SWC changes during  
492 drying per unit of change in SWSI. The smaller the AvS, the smaller the change in SWC and

493 in the associated amount of water released. The AvS is thus related to SWR. The intercept  
494 was obtained when SWSI equaled zero, which was at saturation for FWHM and corresponded  
495 to the theoretical value of SWC at saturation. According to Soltani et al. (2019), the intercept  
496 and the AvS appeared relevant for studying the effects of texture and SOC content on SWR  
497 properties. Therefore, the distribution and relative positions of soil samples on the plane of the  
498 intercept vs. AvS graph result from the combination of their respective porosity and SWR  
499 capacity. In the present study, only soil depth and fertilizer under CT had a significant effect  
500 on the intercept and therefore on SWR properties, and on WHC in particular. Overall,  
501 compared to T0, CT treatments had the largest mean intercept and mean AvS, which indicated  
502 an overall positive effect of tillage on SWR properties and soil porosity. Moreover, the  
503 correlation matrix showed significant positive correlations between WHC,  $S_{Dexter}$  and the two  
504 parameters (intercept, AvS). This thus explains the overall consistency observed between soil  
505 sample distribution on the plane and the effects of agricultural practices on physical and  
506 chemical parameters (e.g. porosity, WHC,  $S_{Dexter}$ , BD, SOC content). For example, cattle  
507 manure fertilization and the increase in SOC content had a pronounced effect on the intercept  
508 and the AvS under CT, which also had the highest WHC. These significant correlations  
509 strengthen the hypothesis that the AvS and the intercept are relevant for assessing the effects  
510 of agricultural practices on soil physical properties.

511 The soil under CTC at 15-25 cm had a larger intercept and AvS than at T0 or under STM and  
512 STC, at both depths. Thus, this soil was assumed to have better structure and physical quality  
513 than the other soil samples. This was reflected in its poral distribution that allowed i) water to  
514 be easily available, since it had higher SWC variation for a SWSI unit variation and, ii) higher  
515  $S_{Dexter}$  and WHC, likely in combination with the increase in SOC content due to cattle manure  
516 input. At 0-15 cm, according to Dexter's criterion, both T0 and CTM had good physical  
517 quality. Soil quality was even better for T0, which had a higher  $S_{Dexter}$ . However, the relative

518 position of CTM on the plane with respect to T0 pointed to the opposite conclusion. Indeed,  
519 CTM had a higher AvS and intercept. The same observation can be made with T0 and STM at  
520 15-25 cm when comparing their  $S_{Dexter}$  and their relative position on the plane. Soil physical  
521 quality is multifactorial and therefore not straightforward to evaluate. Thus, a single index,  
522 such as  $S_{Dexter}$ , may be insufficient to characterize this quality. The plane has an advantage  
523 since it offers a bidimensional approach combining SWR properties and poral distribution,  
524 through the use of intercept and Avs coordinates, to evaluate the physical quality. However,  
525 for this plane to be even more relevant, thresholds must be defined for both the AvS and the  
526 intercept, thus making it possible to characterize soil physical quality.

## 527 **5. Conclusion**

528 In the present study, we used two approaches to study the effects of five years of tillage and  
529 fertilization on SWR properties and soil structural quality. The first approach consisted of  
530 using soil physical, chemical and SWR properties to assess the effects of agricultural practices  
531 on SWR properties and then on soil structural quality. The second approach used spectral soil  
532 information to study the effects of tillage and fertilization on SWR properties and structural  
533 quality. This second approach is derived from results obtained by Soltani et al. (2019), based  
534 on the water characteristic absorption band near 1920 nm. We further compared the results of  
535 the two approaches.

536 Five years of tillage combined with mineral and organic fertilization significantly impacted  
537 SWR properties. CT generally had a more positive effect on SWR properties than T0 and this  
538 effect was more pronounced with organic than with mineral fertilization and at 15-25cm.  
539 SWC, WHC and porosity were greater under CTC than under either CTM or T0.  $S_{Dexter}$  under  
540 CTC was also greater than under CTM and at T0, indicating a generally positive effect on  
541 physical soil quality, but the difference was not significant. However, ST appeared to have a

542 more negative effect on SWR properties than at T0, and cattle manure fertilization did not  
543 lead to a significant increase in SWR properties compared to T0 or STM. Overall, fertilization  
544 had no significant effect on soil properties, which directly influence SWR. Nevertheless,  
545 cattle manure fertilization played an important role in improving the physical quality of tilled  
546 soils. To achieve these results, several soil properties were analyzed, but similar results have  
547 been achieved when analyzing only NIR spectral properties of soil. Our results suggest that  
548 the AvS and the intercept of the linear relation between SWSI and SWC were relevant for  
549 studying the effects of tillage type and fertilization type on SWR properties and soil structural  
550 quality. What is more, plotting the intercept vs. AvS offers a way to summarize and assess the  
551 impacts of agricultural practices on these properties. An increase in the intercept and AvS was  
552 generally associated with an improvement in soil quality.

553 Our findings suggest that spectral information, as a promising alternative approach, can be  
554 used to assess SWR properties and soil structural quality. Reflectance is a dynamic soil  
555 property that can change rapidly due to changes in soil composition, compaction, structural  
556 degradation and biological processes. Using spectral data, one can infer a variety of soil  
557 properties that may influence SWR properties and soil quality. Since five years is a medium-  
558 term time horizon, some effects were not significantly discriminated. It thus appears that our  
559 alternative method would likely be even more relevant in long-term trials. Along with  
560 reflectance, the SWR curve (SWC vs. pressure head) is one of the key soil characteristics that  
561 convey a great deal of soil information. For example,  $S_{Dexter}$  is theoretically derived from the  
562 inflection point of the SWR curve. Estimating hydraulic properties at multiple locations, even  
563 within an agricultural field, is time-consuming and costly. Nevertheless, in the present study,  
564 NIR spectroscopy showed promising results for studying SWR properties. Therefore, further  
565 research could focus on estimating SWSI to predict the SWR curve.

566

567 **Acknowledgements**

568 The EFELE field experiment forms part of the SOERE-PRO (network of long-term  
569 experiments dedicated to the study of impacts of organic waste product recycling). It is  
570 certified by ALLENI (Alliance Nationale de Recherche pour l'Environnement) and  
571 integrated as a service of the “Investment d’Avenir” infrastructure AnaEE-France, overseen  
572 by the French National Research Agency (ANR-11-INBS-0001). The authors are grateful to  
573 T. Morvan for providing access to the EFELE site and to F. Gaillard for assistance with  
574 fieldwork. The authors also appreciate the help provided by Ms. P. Breger and Mr. R. Dubois  
575 during sample collection, measurements of soil retention properties and spectral acquisition in  
576 the laboratory. The first author is supported by a Ph.D. grant from the Tunisian Republic.

577 **References**

- 578 Abiven, S., Menasseri, S., Chenu, C., 2009. The effects of organic inputs over time on soil aggregate  
579 stability – A literature analysis. *Soil Biology and Biochemistry* 41, 1-12.  
580 10.1016/j.soilbio.2008.09.015.
- 581 Abrol, I.P., Palta, J.P., 1968. Bulk density determination of soil clods using rubber solution as a  
582 coating material. *Soil Science* 106, 465–468. <https://doi.org/10.1097/00010694-196812000-00010>.
- 583 AFNOR, 1992. Norme X31–505. Qualité des sols—Méthodes physiques—Méthode de détermination  
584 du volume apparent et du contenu en eau des mottes. Association Française de Normalisation, Paris–  
585 La défense.
- 586 AFNOR, 1998. Norme NF ISO 11274. Qualité du sol—Détermination de la caractéristique de la  
587 rétention en eau—Méthodes de laboratoire. Association Française de Normalisation, Paris–La défense.
- 588 Ahuja, L.R., Fiedler, F., Dunn, G.H., Benjamin, J.G., Garrison, A., 1998. Changes in soil water  
589 retention curves due to tillage and natural reconsolidation. *Soil Science Society of America Journal* 62,  
590 1228–1233. <https://doi.org/10.2136/sssaj1998.03615995006200050011x>.

591 Alvarez, R., Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical  
592 properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil and Tillage*  
593 *Research* 104, 1–15. <https://doi.org/10.1016/j.still.2009.02.005>.

594 Azooz, R.H., Arshad, M.A., 2001. Soil water drying and recharge rates as affected by tillage under  
595 continuous barley and barley–canola cropping systems in northwestern Canada. *Canadian Journal of*  
596 *Soil Science* 81, 45–52. <https://doi.org/10.4141/cjss2013-015>.

597 Babaeian, E., Homae, M., Montzka, C., Vereecken, H., Norouzi, A.A., 2015a. Towards retrieving  
598 soil hydraulic properties by hyperspectral remote sensing. *Vadose Zone Journal* 14.  
599 <https://doi.org/10.2136/vzj2014.07.0080>.

600 Babaeian, E., Homae, M., Vereecken, H., Montzka, C., Norouzi, A.A., van Genuchten, M.T., 2015b.  
601 A comparative study of multiple approaches for predicting the soil-water retention curve:  
602 hyperspectral information vs. basic soil properties. *Soil Science Society of America Journal* 79, 1043–  
603 1058. <https://doi.org/10.2136/sssaj2014.09.0355>.

604 Bai, Z., Caspari, T., Gonzalez, M.R., Batjes, N.H., Mäder, P., Bünemann, E.K., et al., 2018. Effects of  
605 agricultural management practices on soil quality: A review of long-term experiments for Europe and  
606 China. *Agriculture, Ecosystems & Environment* 265, 1-7. [10.1016/j.agee.2018.05.028](https://doi.org/10.1016/j.agee.2018.05.028).

607 Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical  
608 protection and tillage. *Soil and Tillage Research* 53, 215–230. <https://doi.org/10.1016/S0167->  
609 [1987\(99\)00107-5](https://doi.org/10.1016/S0167-1987(99)00107-5).

610 Bescansa, P., Imaz, M.J., Virto, I., Enrique, A., Hoogmoed, W.B., 2006. Soil water retention as  
611 affected by tillage and residue management in semiarid Spain. *Soil and Tillage Research* 87, 19–27.  
612 <https://doi.org/10.1016/j.still.2005.02.028>.

613 Bottinelli, N., Angers, D.A., Hallaire, V., Michot, D., Le Guillou, C., Cluzeau, D., et al., 2017. Tillage  
614 and fertilization practices affect soil aggregate stability in a humic cambisol of northwest France. *Soil*  
615 *and Tillage Research* 170, 14–17. <https://doi.org/10.1016/j.still.2017.02.008>.

616 Cañasveras, J.C., Barrón, V., del Campillo, M.C., Torrent, J., Gómez, J.A., 2010. Estimation of  
617 aggregate stability indices in Mediterranean soils by diffuse reflectance spectroscopy. *Geoderma* 158,  
618 78–84. <https://doi.org/10.1016/j.geoderma.2009.09.004>.

619 Clark, R.N., Roush, T.L., 1984. Reflectance spectroscopy: Quantitative analysis techniques for remote  
620 sensing applications. *Journal of Geophysical Research: Solid Earth* 89, 6329–6340.  
621 <https://doi.org/10.1029/JB089iB07p06329>.

622 Czyż, E.A., Dexter, A.R., 2008. Soil physical properties under winter wheat grown with different  
623 tillage systems at selected locations. *International Agrophysics* 22, 191–200.

624 Dalal, R.C., Henderson, P.A., Glasby, J.M., 1991. Organic matter and microbial biomass in a vertisol  
625 after 20 yr of zero-tillage. *Soil Biology and Biochemistry* 23, 435–441. [https://doi.org/10.1016/0038-](https://doi.org/10.1016/0038-0717(91)90006-6)  
626 [0717\(91\)90006-6](https://doi.org/10.1016/0038-0717(91)90006-6).

627 Dexter, A.R., 2004a. Soil physical quality — Part I. Theory, effects of soil texture, density, and  
628 organic matter, and effects on root growth. *Geoderma* 120, 201–214.  
629 <https://doi.org/10.1016/j.geodermaa.2003.09.005>.

630 Dexter, A.R., 2004b. Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. *Geoderma*  
631 120, 215–225. <https://doi.org/10.1016/j.geoderma.2003.09.005>.

632 Ferreras, L.A., Costa, J.L., Gracia, F.O., Pecorari, C., 2000. Effect of no-tillage on some soil physical  
633 properties of a structural degraded petrocalcic paleudoll of the southern "pampa" of Argentina. *Soil*  
634 *and Tillage Research* 54, 31–39. [https://doi.org/10.1016/S0167-1987\(99\)00102-6](https://doi.org/10.1016/S0167-1987(99)00102-6).

635 Gomez, C., Le Bissonnais, Y., Annabi, M., Bahri, H., Raclot, D., 2013. Laboratory Vis–NIR  
636 spectroscopy as an alternative method for estimating the soil aggregate stability indexes of  
637 Mediterranean soils. *Geoderma* 209–210, 86–97. <https://doi.org/10.1016/j.geoderma.2013.06.002>.

638 Green, T.R., Ahuja, L.R., Benjamin, J.G., 2003. Advances and challenges in predicting agricultural  
639 management effects on soil hydraulic properties. *Geoderma* 116, 3–27. [https://doi.org/10.1016/s0016-](https://doi.org/10.1016/s0016-7061(03)00091-0)  
640 [7061\(03\)00091-0](https://doi.org/10.1016/s0016-7061(03)00091-0).

641 Green, V., Stott, D., Cruz, J., Curi, N., 2007. Tillage impacts on soil biological activity and  
642 aggregation in a Brazilian Cerrado Oxisol. *Soil and Tillage Research* 92, 114–121.  
643 <https://doi.org/10.1016/j.still.2006.01.004>.

644 Guérif, J., Richard, G., Durr, C., Machet, J.M., Recous, S., Roger-Estrade, J., 2001. A review of tillage  
645 effects on crop residue management, seedbed conditions and seedling establishment. *Soil and Tillage*  
646 *Research* 61, 13–32. [https://doi.org/10.1016/S0167-1987\(01\)00187-8](https://doi.org/10.1016/S0167-1987(01)00187-8).

647 IPBES, 2018. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.  
648 The assessment report of land degradation and restoration, p. 965. [https://www.ipbes.net/assessment-](https://www.ipbes.net/assessment-reports/ldr)  
649 [reports/ldr](https://www.ipbes.net/assessment-reports/ldr).

650 Janik, L.J., Forrester, S.T., Rawson, A., 2009. The prediction of soil chemical and physical properties  
651 from mid-infrared spectroscopy and combined partial least-squares regression and neural networks  
652 (PLS-NN) analysis. *Chemometrics and Intelligent Laboratory Systems* 97, 179–188.  
653 <https://doi.org/10.1016/j.chemolab.2009.04.005>.

654 Jarvis, N.J., 2007. A review of non-equilibrium water flow and solute transport in soil macropores:  
655 principles, controlling factors and consequences for water quality. *Eur. J. Soil Sci.* 58, 523–546.  
656 <https://doi.org/10.1111/j.1365-2389.2007.00915.x>.

657 Jiao, Y., Whalen, J.K., Hendershot, W.H., 2006. No-tillage and manure applications increase  
658 aggregation and improve nutrient retention in a sandy-loam soil. *Geoderma* 134, 24-33.  
659 [10.1016/j.geoderma.2005.08.012](https://doi.org/10.1016/j.geoderma.2005.08.012).

660 Kabiri, V., Raiesi, F., Ghazavi, M.A., 2015. Six years of different tillage systems affected aggregate-  
661 associated SOM in a semi-arid loam soil from Central Iran. *Soil and Tillage Research* 154, 114–125.  
662 <https://doi.org/10.1016/j.still.2015.06.019>.

663 Kirkham, M.B., 2014. Chapitre10-Field Capacity, Wilting Point, Available Water, and the  
664 Nonlimiting Water Range, In: Kirkham, M.B. (Ed.), *Principles of Soil and Plant Water Relations*  
665 (Second Edition). Academic Press, Oxford, UK, pp. 153-170.

666 Larney, F.J., Angers, D.A., 2012. The role of organic amendments in soil reclamation: A review.  
667 *Canadian Journal of Soil Science* 92, 19–38.

668 Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration  
669 as influenced by tillage methods. *Soil and Tillage Research* 89, 210–220.  
670 <https://doi.org/10.1016/j.still.2005.07.012>.

671 Lipiec, J., Nosalewicz, A., 2004. The effects of soil compaction on plant root growth, function and  
672 stomatal diffusive resistance, In: Lipiec, J., Nosalewicz, A., Józefaciuk, G. (Eds.), *Plant growth in*  
673 *relation to soil physical conditions*. IA PAS Press, Lublin, Poland, pp. 86–94.

674 Liu, Y., Gao, M., Wu, W., Tanveer, S.K., Wen, X., Liao, Y., 2013. The effects of conservation tillage  
675 practices on the soil water-holding capacity of a non-irrigated apple orchard in the Loess Plateau,  
676 China. *Soil and Tillage Research* 130, 7–12. <https://doi.org/10.1016/j.still.2013.01.012>.

677 Mahmoodlu, M.G., Raoof, A., Sweijen, T., van Genuchten, M.T., 2016. Effects of sand compaction  
678 and mixing on pore structure and the unsaturated soil hydraulic properties. *Vadose Zone Journal* 15.  
679 <https://doi.org/10.2136/vzj2015.10.0136>.

680 Maillard, E., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: a meta-  
681 analysis. *Glob Chang Biol* 20, 666-679. 10.1111/gcb.12438.

682 Mikha, M.M., Rice, C.W., 2004. Tillage and manure effects on soil and aggregate-associated carbon  
683 and nitrogen. *Soil Science Society of America Journal* 68, 809-816. 10.2136/sssaj2004.8090.

684 Minasny, B., Malone, B., Stockmann, U., Odgers, N., McBratney, A.B., 2014. Pedometrics. Reference  
685 Module in Earth Systems and Environmental Sciences. [https://doi.org/10.1016/b978-0-12-409548-](https://doi.org/10.1016/b978-0-12-409548-9.09163-6)  
686 [9.09163-6](https://doi.org/10.1016/b978-0-12-409548-9.09163-6).

687 Moret, D., Arrúe, J.L., 2007. Characterizing soil water-conducting macro- and mesoporosity as  
688 influenced by tillage using tension infiltrometry. *Soil Science Society of America Journal* 71, 500–  
689 506. <https://doi.org/10.2136/sssaj2006.0128>.

690 Mouazen, A.M., Kuang, B., De Baerdemaeker, J., Ramon, H., 2010. Comparison among principal  
691 component, partial least squares and back propagation neural network analyses for accuracy of  
692 measurement of selected soil properties with visible and near infrared spectroscopy. *Geoderma* 158,  
693 23-31. 10.1016/j.geoderma.2010.03.001.

694 Naderi-Boldaji, M., Keller, T., 2016. Degree of soil compactness is highly correlated with the soil  
695 physical quality index S. *Soil and Tillage Research* 159, 41–46.  
696 <https://doi.org/10.1016/j.still.2016.01.010>.

697 Nocita, M., Stevens, A., Noon, C., van Wesemael, B., 2013. Prediction of soil organic carbon for  
698 different levels of soil moisture using Vis-NIR spectroscopy. *Geoderma* 199, 37–42.  
699 <https://doi.org/10.1016/j.geoderma.2012.07.020>.

700 Osunbitan, J.A., Oyedele, D.J., Adekalu, K.O., 2005. Tillage effects on bulk density, hydraulic  
701 conductivity and strength of a loamy sand soil in southwestern Nigeria. *Soil and Tillage Research* 82,  
702 57–64. <https://doi.org/10.1016/j.still.2004.05.007>.

703 Richard, G., Sillon, J.F., Cousin, I., Bruand, A., 2004. Travail du sol, structure et fonctionnement  
704 hydrique du sol en régime d'évaporation. *Etude et gestion des sols, association française pour l'étude*  
705 *des sols* 11, 59–68.

706 Roger-Estrade, J., Anger, C., Bertrand, M., Richard, G., 2010. Tillage and soil ecology: Partners for  
707 sustainable agriculture. *Soil and Tillage Research* 111, 33-40.  
708 <https://doi.org/10.1016/j.still.2010.08.010>.

709 Salem, H.M., Valero, C., Muñoz, M.Á., Rodríguez, M.G., Silva, L.L., 2015. Short-term effects of four  
710 tillage practices on soil physical properties, soil water potential, and maize yield. *Geoderma* 237–238,  
711 60–70. <https://doi.org/10.1016/j.geoderma.2014.08.014>.

712 Santra, P., Sahoo, R.N., Das, B.S., Samal, R.N., Pattanaik, A.K., Gupta, V.K., 2009. Estimation of soil  
713 hydraulic properties using proximal spectral reflectance in visible, near-infrared, and shortwave-  
714 infrared (VIS–NIR–SWIR) region. *Geoderma* 152, 338–349.  
715 <https://doi.org/10.1016/j.geoderma.2009.07.001>.

716 Sarathjith, M.C., Das, B.S., Vasava, H.B., Mohanty, B., Sahadevan, A.S., Wani, S.P., et al., 2014.  
717 Diffuse reflectance spectroscopic approach for the characterization of soil aggregate size distribution.  
718 *Soil Science Society of America Journal* 78, 369. <https://doi.org/10.2136/sssaj2013.08.0377>.

719 Six, J., Feller, C., Denef, K., Ogle, S.M., de Moraes, J.C., Albrecht, A., 2002. Soil organic matter,  
720 biota and aggregation in temperate and tropical soils—effects of no-tillage. *Agronomie* 22, 755–775.  
721 <https://doi.org/10.1051/agro:2002043>.

722 Soltani, I., Fouad, Y., Michot, D., Bréger, P., Dubois, R., Cudennec, C., 2019. A near infrared index to  
723 assess effects of soil texture and organic carbon content on soil water content. *Eur. J. Soil Sci.* 70, 151-  
724 161. [10.1111/ejss.12725](https://doi.org/10.1111/ejss.12725).

725 Soriano-Disla, J.M., Janik, L.J., Viscarra Rossel, R.A., MacDonald, L.M., McLaughlin, M.J., 2014.  
726 The performance of visible, near-, and mid-infrared reflectance spectroscopy for prediction of soil

727 physical, chemical, and biological properties. *Applied Spectroscopy Reviews* 49, 139–186.  
728 <https://doi.org/10.1080/05704928.2013.811081>.

729 Strudley, M., Green, T., Ascoughii, J., 2008. Tillage effects on soil hydraulic properties in space and  
730 time: State of the science. *Soil and Tillage Research* 99, 4–48.  
731 <https://doi.org/10.1016/j.still.2008.01.007>.

732 Tauro, F., Selker, J., van de Giesen, N., Abrate, T., Uijlenhoet, R., Porfiri, M., et al., 2018.  
733 Measurements and Observations in the XXI century (MOXXI): innovation and multi-disciplinarity to  
734 sense the hydrological cycle. *Hydrological Sciences Journal* 63, 169–196.  
735 <https://doi.org/10.1080/02626667.2017.1420191>.

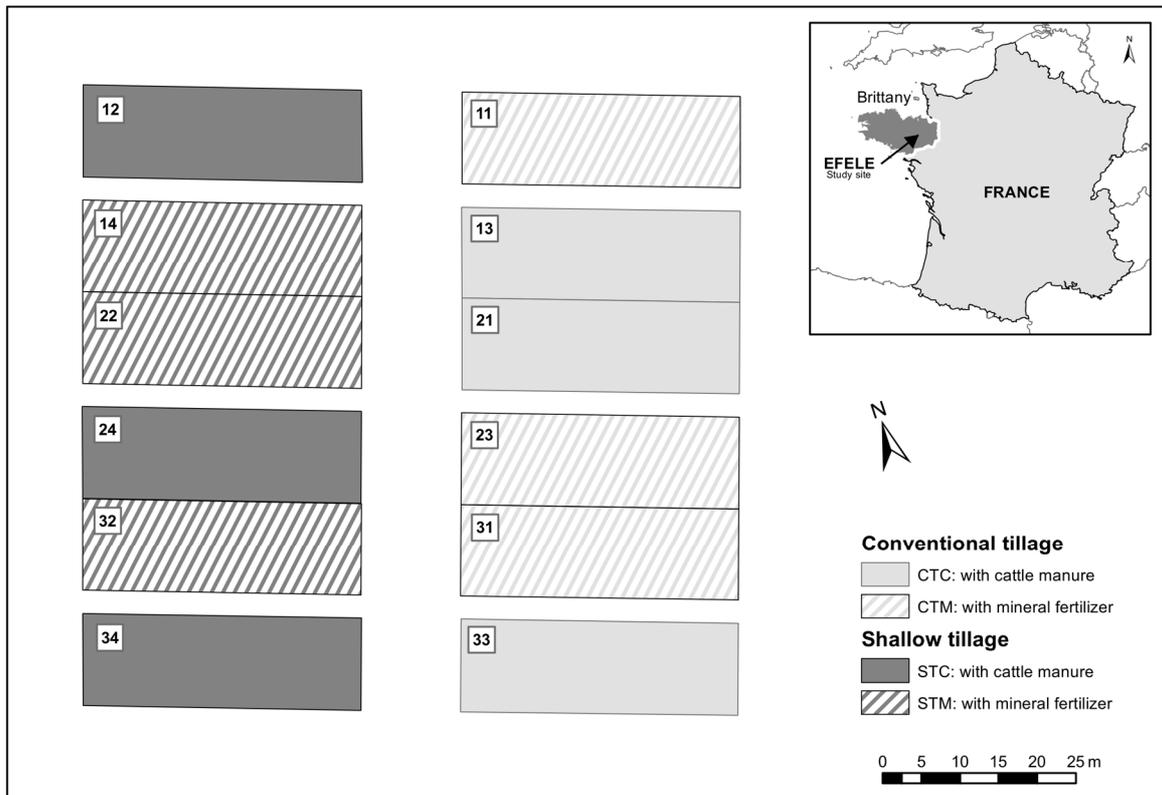
736 Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of  
737 unsaturated soils. *Soil Science Society of America Journal* 44, 892–898.  
738 <https://doi.org/10.2136/sssaj1980.03615995004400050002x>.

739 Viscarra Rossel, R.A., Behrens, T., 2010. Using data mining to model and interpret soil diffuse  
740 reflectance spectra. *Geoderma* 158, 46–54. <https://doi.org/10.1016/j.geoderma.2009.12.025>.

741

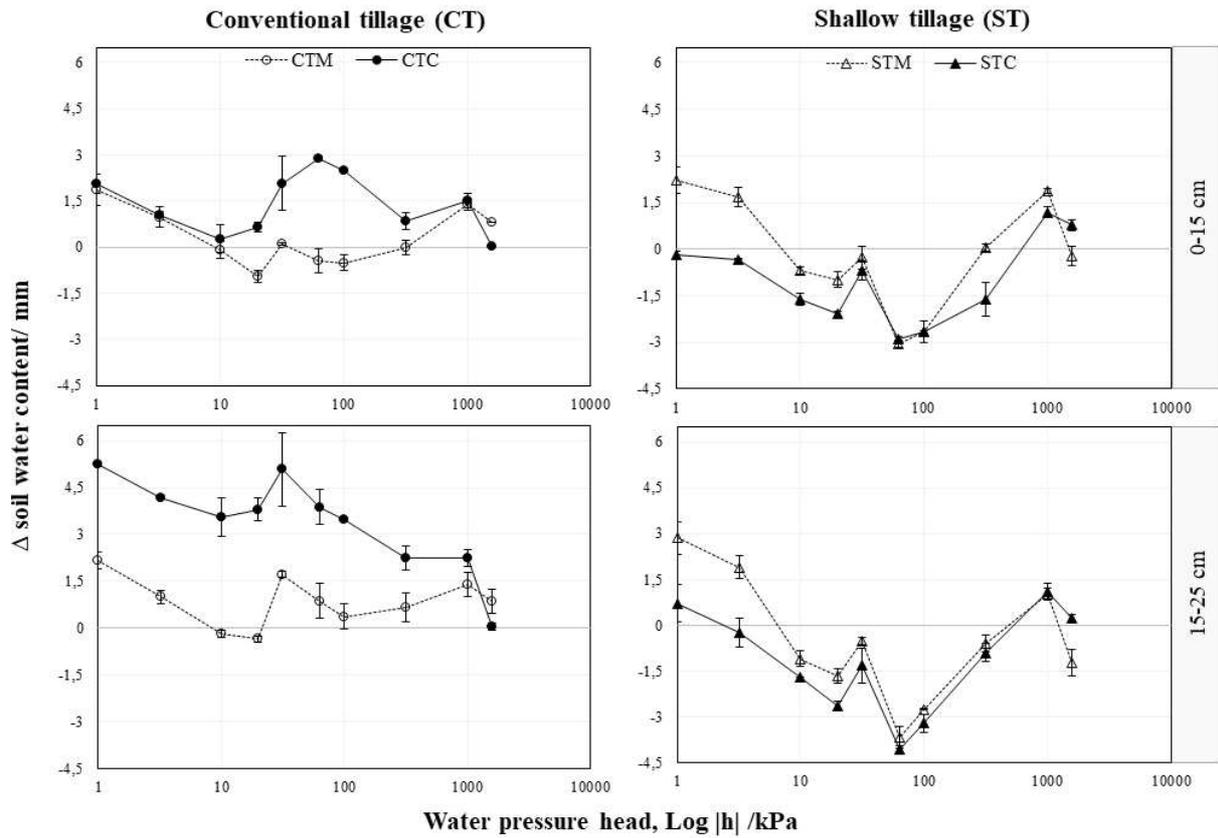
742

1 **Figure 1.** Location of the EFELE experimental site and the experimental plot design (plots  
2 are marked by identification number)



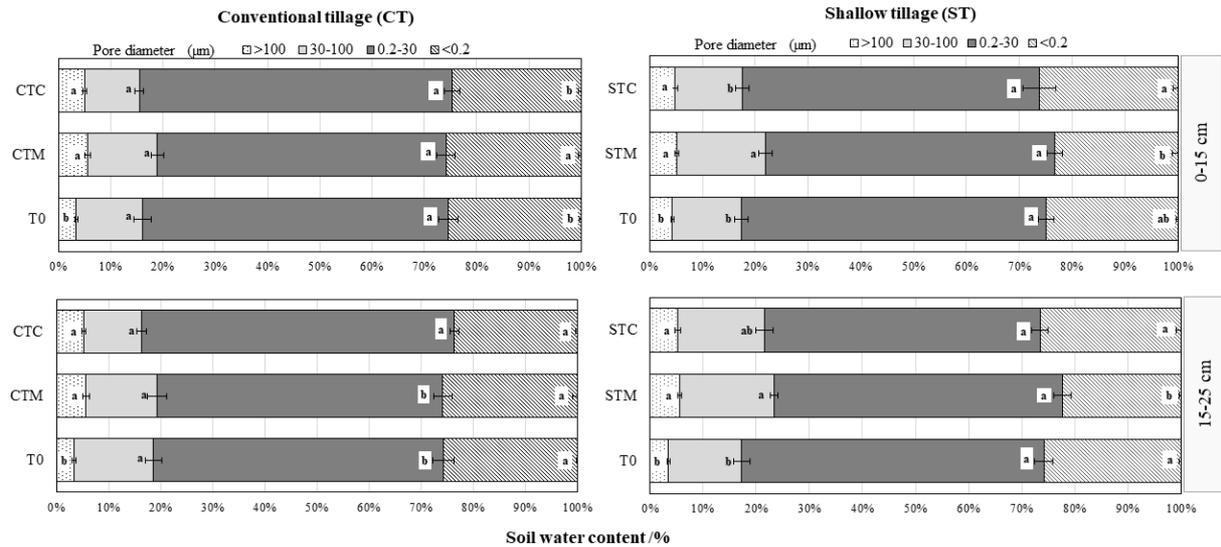
3  
4  
5  
6  
7  
8

9 **Figure 2.** Difference between mean soil water content under four treatments (CTC, CTM,  
 10 STC and STM) and at the initial state (T0) as a function of pressure head. Error bars indicate  
 11 1 standard error. STM is shallow tillage with mineral fertilizer; STC is shallow tillage with  
 12 cattle manure; CTM is conventional tillage with mineral fertilizer and CTC is conventional  
 13 tillage with cattle manure



14  
 15  
 16  
 17  
 18  
 19

20 **Figure 3.** Pore-size distribution of soil samples at two depths at the initial state (T0) and  
 21 under four treatments: STM, shallow tillage with mineral fertilizer; STC, shallow tillage with  
 22 cattle manure; CTM, conventional tillage with mineral fertilizer; CTC, conventional tillage  
 23 with cattle manure. Error bars indicate 1 standard error. Values with different letters are  
 24 significantly different ( $P < 0.05$ ) according to ANOVA.

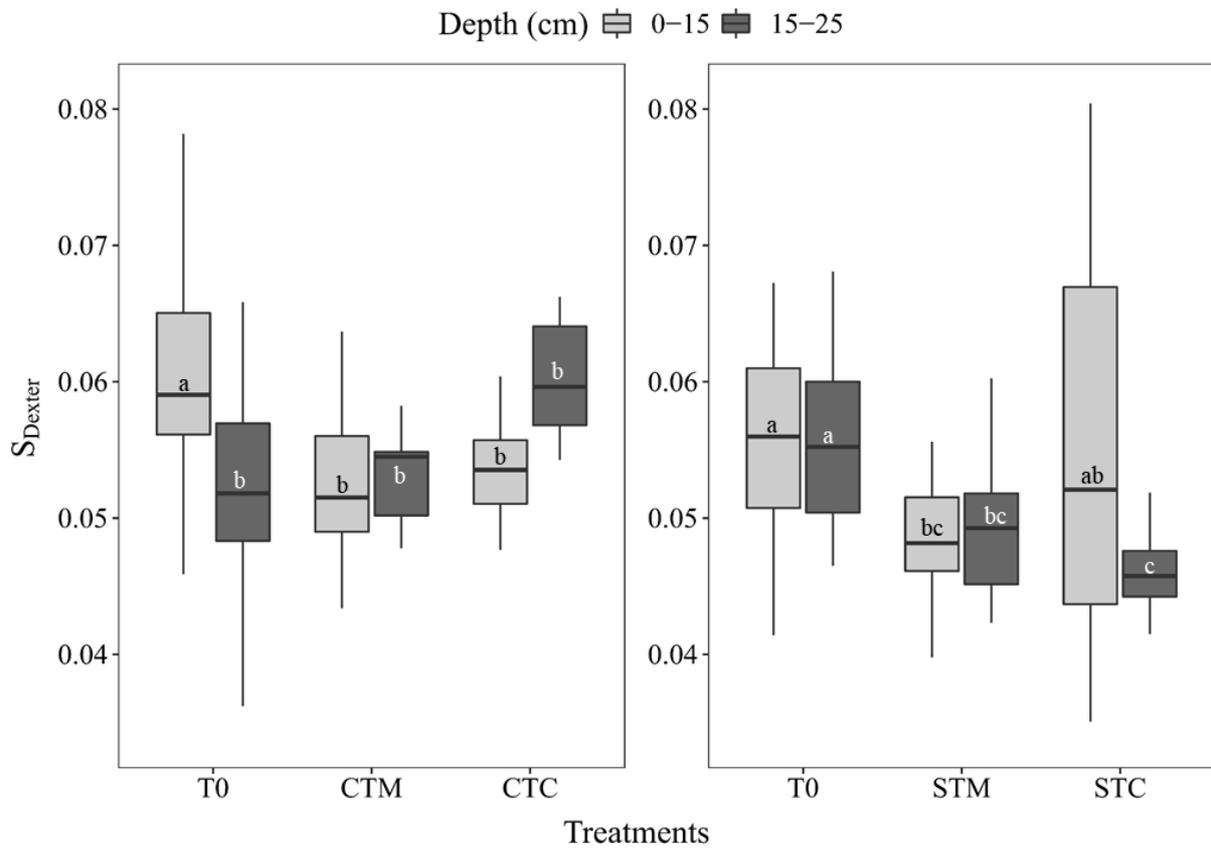


25

26

27

28 **Figure 4.** The  $S_{Dexter}$  index of soil physical quality at two depths (0-15 and 15-25cm) before  
 29 (T0) and after five years of treatment (STM, STC, CTM and CTC). Whiskers represent 1.5  
 30 times the interquartile range. Values with different letters are significantly different ( $P < 0.05$ )  
 31 according to ANOVA. STM is shallow tillage with mineral fertilizer; STC is shallow tillage  
 32 with cattle manure; CTM is conventional tillage with mineral fertilizer and CTC is  
 33 conventional tillage with cattle manure

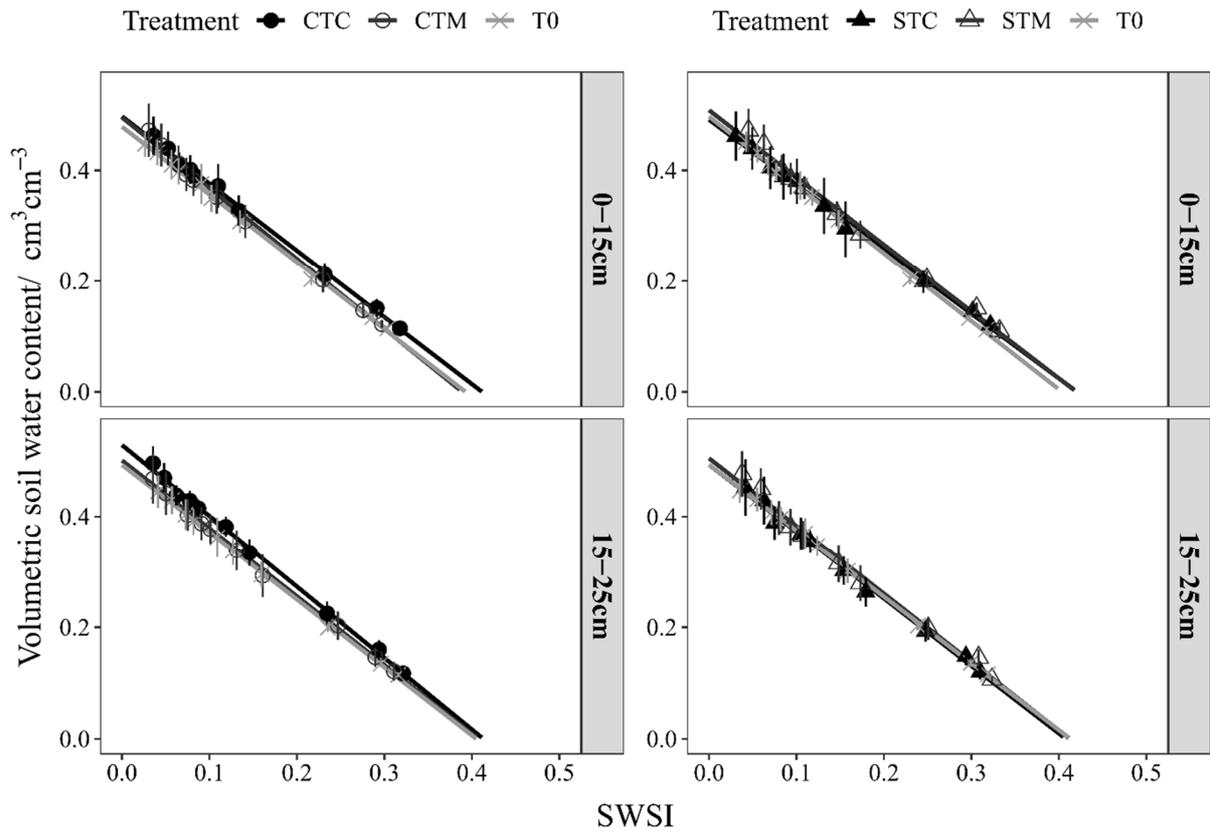


34

35

36

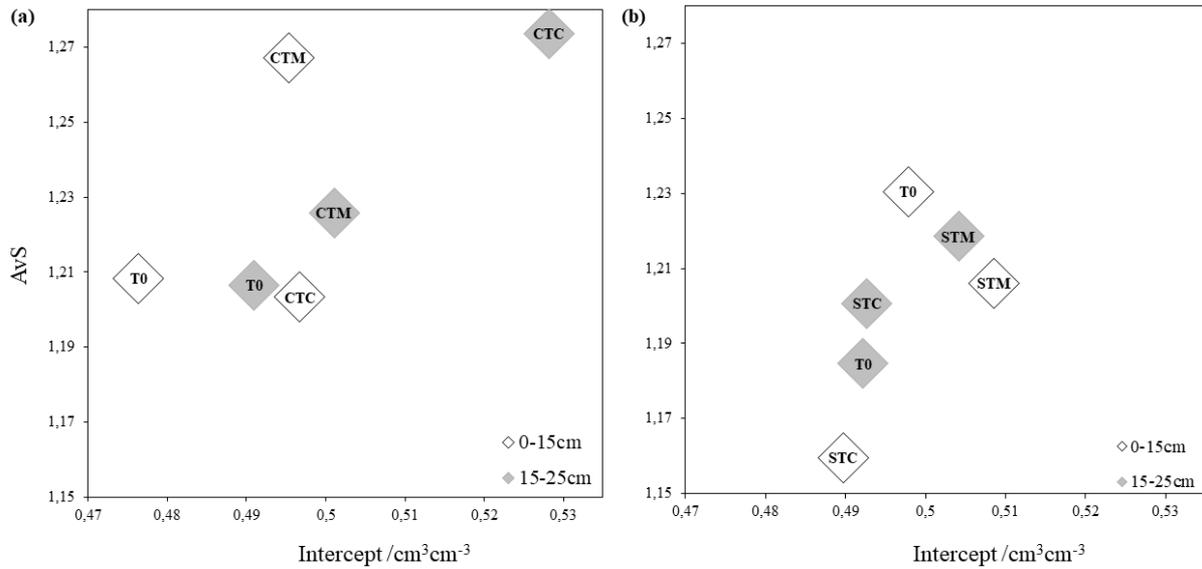
37 **Figure 5.** Soil water content at two depths (0-15 and 15-25cm) as a function of the soil water  
 38 spectral index (SWSI) for four treatments: a) mineral fertilization with shallow tillage (STM)  
 39 and conventional tillage (CTM); b) cattle manure fertilization with shallow tillage (STC) and  
 40 conventional tillage (CTC). Treatments are compared to samples from T0, the initial state  
 41 before tillage and fertilization began in 2012.



42

43

44 **Figure 6.** Mean intercept vs. mean absolute value of the slope (AvS) of the relationship  
 45 between the soil water spectral index and soil water content at the initial state (T0) and under  
 46 four treatments at two depths (0-15 and 15-25cm). STM is shallow tillage with mineral  
 47 fertilizer; STC is shallow tillage with cattle manure; CTM is conventional tillage with mineral  
 48 fertilizer and CTC is conventional tillage with cattle manure.



49  
 50  
 51  
 52  
 53

1 **Table 1**

2 Results of two-way ANOVA with depth and fertilization as fixed effects on soil organic carbon content and bulk density under conventional and  
 3 shallow tillage.

Source of variation	Degrees of freedom	Soil organic carbon content				Bulk density			
		Sum of squares	Mean squares	<i>F ratio</i>	<i>P</i>	Sum of squares	Mean squares	<i>F ratio</i>	<i>P</i>
Conventional tillage (CT)									
Depth	1	2.574	2.5742	10.323	0.0048	0.002558	0.002558	1.704	0.20821
Fertilizer	2	1.14	0.5701	2.286	0.1304	0.023558	0.011779	7.847	0.00354
D*F	2	0.13	0.0651	0.261	0.7732	0.000049	0.000024	0.016	0.98396
Residuals	18	4.488	0.2494			0.02702	0.001501		
Total	23	8.332	3.4588			0.053185	0.015862		
Shallow tillage (ST)									
Depth	1	9.375	9.375	84.144	3.31E-08	0.00151	0.001513	0.857	0.367
Fertilizer	2	1.241	0.62	5.568	0.0131	0.00683	0.003414	1.934	0.173
D*F	2	5.501	2.75	24.686	6.94E-06	0.00462	0.002311	1.309	0.294
Residuals	18	2.005	0.111			0.03177	0.001765		
Total	23	18.122	12.856			0.04473	0.009003		

4

5

6

7 **Table 2**

8 The effect of agricultural practices on soil bulk density and soil organic carbon content at depths of 0-15 cm and 15-25 cm, compared to the  
 9 initial state (T0). The T0 values are averaged for all 6 plots, while the values for each treatment are averaged for its 3 plots.

	Conventional tillage			Shallow tillage		
	T0	CTM	CTC	T0	STM	STC
Soil organic carbon content (g kg <sup>-1</sup> )						
0-15 cm	11.0 (0.2) <sup>a,a</sup>	10.8 (0.2) <sup>a,a</sup>	11.5 (0.3) <sup>a,a</sup>	10.4 (0.2) <sup>c,a</sup>	11.3 (0.2) <sup>b,a</sup>	12.1 (0.2) <sup>a,a</sup>
15-25 cm	10.3 (0.3) <sup>a,b</sup>	10.4 (0.2) <sup>a,a</sup>	10.8 (0.3) <sup>a,a</sup>	10.1 (0.1) <sup>a,a</sup>	9.4 (0.2) <sup>b,b</sup>	9.6 (0.1) <sup>b,b</sup>
Bulk density						
0-15 cm	1.56 (0.02) <sup>a,a</sup>	1.62 (0.01) <sup>a,a</sup>	1.62 (0.02) <sup>a,a</sup>	1.58 (0.01) <sup>a,a</sup>	1.61 (0.02) <sup>a,a</sup>	1.59 (0.03) <sup>a,a</sup>
15-25 cm	1.54 (0.02) <sup>a,a</sup>	1.60 (0.02) <sup>a,a</sup>	1.59 (0.00) <sup>a,a</sup>	1.55 (0.02) <sup>a,a</sup>	1.57 (0.02) <sup>a,a</sup>	1.62 (0.04) <sup>a,a</sup>

10 Values with different letters are significantly different ( $P < 0.05$ ) according to ANOVA. Values with the same letter within each row belong the same homogeneous group  
 11 according to Fisher's least significant difference test, and values without letters do not differ among treatments. Different first letters indicate a significant difference between  
 12 treatments, whereas different second letters indicate a significant difference between depths for the same treatment. Standard errors of means are indicated in parentheses.  
 13 STM is shallow tillage with mineral fertilizer; STC is shallow tillage with cattle manure; CTM is conventional tillage with mineral fertilizer and CTC is conventional tillage  
 14 with cattle manure.

15

16 **Table 3**

17 The effects of depth and fertilization treatments on soil water content (SWC) and water holding capacity (WHC) at three pressure heads (near  
 18 saturation (–3.2 kPa), field capacity (–31.6 kPa) and permanent wilting point (–1585 kPa)), compared to the initial state (T0) under conventional  
 19 and shallow tillage.

Matric potential (kPa)	Conventional tillage (CT)			Shallow tillage (ST)		
	T0	CTM	CTC	T0	STM	STC
	0-15 cm					
SWC (cm <sup>3</sup> cm <sup>-3</sup> )						
–3.2	0.432 (0.005) <sup>a</sup>	0.446 (0.011) <sup>a</sup>	0.439 (0.009) <sup>a</sup>	0.432 (0.004) <sup>a</sup>	0.448 (0.010) <sup>a</sup>	0.440 (0.011) <sup>a</sup>
–31.6	0.376 (0.008) <sup>a</sup>	0.383 (0.008) <sup>a</sup>	0.391 (0.006) <sup>a</sup>	0.373 (0.006) <sup>a</sup>	0.369 (0.006) <sup>a</sup>	0.380 (0.012) <sup>a</sup>
–1585	0.114 (0.001) <sup>b</sup>	0.122 (0.002) <sup>a</sup>	0.114 (0.002) <sup>b</sup>	0.113 (0.001) <sup>ab</sup>	0.110 (0.004) <sup>b</sup>	0.121 (0.004) <sup>a</sup>
WHC (mm) *						
–31.6 to –1585	26.2 (0.8) <sup>a</sup>	26.1 (0.8) <sup>a</sup>	27.6 (0.7) <sup>a</sup>	26.0 (0.7) <sup>a</sup>	25.9 (0.7) <sup>a</sup>	26.0 (1.4) <sup>a</sup>
	15-25 cm					
SWC (cm <sup>3</sup> cm <sup>-3</sup> )						
–3.2	0.430 (0.006) <sup>b</sup>	0.442 (0.011) <sup>b</sup>	0.470 (0.008) <sup>a</sup>	0.431 (0.005) <sup>a</sup>	0.450 (0.011) <sup>a</sup>	0.429 (0.012) <sup>a</sup>
–31.6	0.362 (0.008) <sup>b</sup>	0.378 (0.008) <sup>b</sup>	0.415 (0.004) <sup>a</sup>	0.370 (0.007) <sup>a</sup>	0.366 (0.008) <sup>a</sup>	0.355 (0.006) <sup>a</sup>
–1585	0.115 (0.001) <sup>a</sup>	0.121 (0.005) <sup>a</sup>	0.117 (0.002) <sup>a</sup>	0.116 (0.002) <sup>a</sup>	0.107 (0.001) <sup>b</sup>	0.120 (0.004) <sup>a</sup>
WHC (mm)*						
–31.6 to –1585	24.8 (0.9) <sup>b</sup>	25.6 (0.8) <sup>b</sup>	29.8 (0.4) <sup>a</sup>	25.4 (0.8) <sup>ab</sup>	25.9 (0.8) <sup>a</sup>	23.5 (0.7) <sup>b</sup>

20 **Notes:** Values with different letters are significantly different ( $P < 0.05$ ) according to ANOVA. Values with the same letter within each row are not significantly different  
 21 according to the probability of mean differences at  $\alpha = 0.05$  with Fisher's least significant difference test. Standard errors of means are indicated in parentheses. STM is  
 22 shallow tillage with mineral fertilizer; STC is shallow tillage with cattle manure; CTM is conventional tillage with mineral fertilizer and CTC is conventional tillage with  
 23 cattle manure.

24 \*WHC was calculated for a standard thickness of 10 cm.

25 **Table 4**

26 The absolute value of the slope and the intercept of the relationship between the soil water spectral index and soil water content for soil samples  
 27 from two depths at the initial state (T0) and under four treatments: STM, shallow tillage with mineral fertilizer; STC, shallow tillage with cattle  
 28 manure; CTM, conventional tillage with mineral fertilizer and CTC, conventional tillage with cattle manure.

	Treatment	Intercept (Se) cm <sup>3</sup> cm <sup>-3</sup>	AvS (Se)	<i>p-value</i>	<i>R</i> <sup>2</sup>
0-15 cm					
CT	T0	0.476 (0.007)	1.21 (0.02)	5.32E-12	98.8
	CTM	0.495 (0.015)	1.27 (0.04)	7.80E-11	99.6
	CTC	0.497 (0.011)	1.20 (0.02)	2.07E-11	99.7
ST	T0	0.498 (0.006)	1.23 (0.02)	3.03E-12	99
	STM	0.509 (0.014)	1.21 (0.03)	1.79E-09	99.1
	STC	0.490 (0.011)	1.16 (0.02)	3.62E-11	99.7
15-25 cm					
CT	T0	0.491 (0.008)	1.21 (0.02)	3.42E-13	99
	CTM	0.501 (0.012)	1.23 (0.03)	2.93E-09	99.8
	CTC	0.528 (0.006)	1.27 (0.01)	3.25E-10	99.7
ST	T0	0.492 (0.007)	1.18 (0.02)	5.41E-13	99
	STM	0.504 (0.012)	1.22 (0.03)	6.34E-12	99
	STC	0.493 (0.017)	1.20 (0.04)	1.71E-11	99.4

29 *Standard errors of means are indicated in parentheses.*

30

31

32 **Table 5**

33 Results of two-way ANOVA of the intercept and absolute value of the slope (AvS) of the relationship between the soil water spectral index and  
 34 soil water content with depth and fertilization as fixed effects under mineral and organic fertilization.

Source of variation	Degrees of freedom	Intercept ( $\text{cm}^3 \text{cm}^{-3}$ )				AvS			
		Sum of squares	Mean squares	<i>F ratio</i>	<i>P</i>	Sum of squares	Mean squares	<i>F ratio</i>	<i>P</i>
Conventional tillage									
Depth	1	0.00598	0.005981	4.512	0.0368	0.0012	0.00118	0.118	0.732
Fertilizer	2	0.0121	0.006048	4.563	0.0134	0.0261	0.013074	1.311	0.275
D*F	2	0.00205	0.001026	0.774	0.4646	0.0389	0.019449	1.95	0.149
Residuals	78	0.10339	0.001326			0.7779	0.009973		
Total	83	0.12352	0.014381			0.8441	0.043676		
Shallow tillage									
Depth	1	0.00017	0.0001701	0.106	7.46E-01	0.0004	0.000399	0.046	0.831
Fertilizer	2	0.00306	0.0015315	0.952	0.39	0.0151	0.007552	0.867	0.424
D*F	2	0.00029	0.0001433	0.089	9.15E-01	0.0297	0.01485	1.706	0.188
Residuals	78	0.12549	0.0016088			0.679	0.008705		
Total	83	0.12901	0.0034537			0.7242	0.031506		

35

36

37 **Table 1**

38 Pearson correlation matrix of the absolute value of the slope (AvS) and intercept of the relationship between the soil water spectral index and soil  
 39 water content and soil properties [soil organic carbon (SOC) content, bulk density (BD), water holding capacity (WHC), and the Dexter index of  
 40 soil physical quality ( $S_{\text{Dexter}}$ )].

	AvS	Intercept	SOC	BD	WHC	$S_{\text{Dexter}}$
AvS	1.00					
Intercept	0.80***	1.00				
SOC	0.07	0.12	1.00			
BD	-0.09	-0.18	-0.06	1.00		
WHC	0.62***	0.64***	0.27*	-0.09	1.00	
$S_{\text{Dexter}}$	0.39**	0.34**	0.21*	-0.25*	0.74***	1.00

41 \*\*\* significant at  $P < 0.001$ ; \*\* significant at  $P < 0.01$ ; \* significant at  $P < 0.05$

42