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1 Long-term effects of conventional tillage and no-tillage on saturated 2 and near-saturated hydraulic conductivity – Can their prediction be 3 improved by pore metrics obtained with X-ray CT?

4 Steffen Schlüter¹, Lukas Albrecht¹, Kai Schwärzel^{2,3}, Janis Kreiselmeier^{2,4}

5 1. Department of Soil System Sciences, Helmholtz-Centre for Environmental Research – UFZ, Halle,
6 Germany

7 2. Institute for Integrated Management of Material Fluxes and of Resources - UNU-FLORES, United
8 Nations University, Dresden, Germany

9 3. Thünen Institute of Forest Ecosystems, Eberswalde, Germany

10 4. Institute of Soil Science and Site Ecology, TU Dresden, Tharandt, Germany

11 Keywords: X-ray tomography; hood infiltrometer; tension disc infiltrometer; Stokes-Brinkmann
12 solver; preferential flow; pedo-transfer functions

13

14 **Abstract**

15 Tillage practices have a profound impact on soil structure and soil hydrology, which may affect
16 ecosystem functions like plant productivity. There is an ongoing debate whether a conversion from
17 conventional tillage (CT) to no-till (NT) leads to an increase in (near-)saturated hydraulic conductivity.
18 This is because true effects are often disguised by large spatial and temporal variability, but also by the
19 deficiencies in the measurement technique.

20 In this paper, we measured (near-) saturated hydraulic conductivity (K_s and K_{-2}) in a long-term tillage trial
21 (26 years) in Germany with three different methods: hood infiltrometer (HI) in the field, tension disk
22 infiltrometer (TI) on undisturbed soil cores and direct simulation (DS) of water flow on X-ray CT images of
23 macropore structure in these soil cores with a Stokes-Brinkmann solver. On average the absolute values
24 varied by two orders of magnitude in the order $TI < HI < DS$ with very low correlation ($R^2 < 0.05$) between
25 $\log_{10}(K_s)$ measurements. The conversion from CT to NT caused an increase in bulk density, a decrease in
26 air capacity and a small but consistent decrease in grain yields. K_s was increased when measured with HI
27 but decreased in TI and indifferent when measured with DS. This inconsistency is caused by the
28 proportion at which large biopores that are more frequent in NT soil due to higher earthworm
29 abundance contribute to total flow in each measurement technique. Regression analyses between pore
30 space attributes measured with X-ray CT and K_s (and K_{-2}) showed very strong agreement with DS values,
31 but poorer agreement with HI and TI, suggesting that those values are afflicted with measurement
32 artifacts like poor contact, entrapped air, different average volumes and so on.

33 The pore metric with highest predictive power (>90%) on simulated K_s in NT soil cores was the critical
34 pore diameter because it represents the bottleneck that restricts a large contribution to flow by
35 elongated biopores. However, in plowed soil (CT) pore metrics that best describe flow through the loose
36 soil matrix, like macroporosity and pore connectivity, have a higher predictive power and the critical

37 pore diameter is rendered meaningless. The relative importance of various pore metrics as good
38 predictors of hydraulic conductivity does not only change in a very small pressure range (K_s vs. K_2) but
39 also between measurement techniques (HI vs. TI vs. DS). These inconsistencies raise the question if and
40 how existing pedo-transfer functions for estimating (near-) saturated hydraulic conductivities can be
41 extended by image-derived pore metrics in a meaningful way.

42 **1. Introduction**

43 The change from conventional to conservation agriculture has many implications for ecosystem
44 functions like water filter and storage, carbon storage and plant production (Palm et al., 2014). There is a
45 whole range of tillage intensities, starting from conventional tillage with a moldboard plow that turns the
46 soil in the plow layer, to reduced (or minimum) tillage with a cultivator or disk harrow that loosens the
47 soil superficially, to no-till or direct drilling, as well as combination thereof in strip tillage (Licht and Al-
48 Kaisi, 2005; Pöhlitz et al., 2018; Tebrügge and Düring, 1999). The farmer's choice on tillage intensity is
49 usually driven by economic interests in terms of expected yields, investments in machinery,
50 agrochemicals fuel and labor costs, but also entails ecological consequences, e.g., in terms of soil
51 degradation, erosion and carbon sequestration (Palm et al., 2014; Soane et al., 2012).

52 The lack of plowing has direct and indirect consequences on soil structure. Usually soil compaction sets
53 in with the conversion to no-till, which can lead to a reduction in air capacity and an increase in bulk
54 density and penetration resistance in the topsoil (Abdollahi et al., 2017; Abdollahi and Munkholm, 2017;
55 Rasmussen, 1999; Rücknagel et al., 2017). However, these trends may vanish when comparing tillage
56 trials across different climates, textures and time scales (Blanco-Canqui and Ruis, 2018). The status of soil
57 physical properties of a NT-system may for example be dependent on the time passed since its
58 establishment (Reichert et al., 2016). Initially macroporosity decreases, while bulk density and
59 microporosity increases. After several years this may reverse through a re-structuring of the soil by
60 bioturbation. Legacy effects also exist for reverse conversion, i.e., a topsoil that is plowed once after a
61 period of conservation tillage has different soil physical properties than continuously plowed topsoils
62 (Kuhwald et al., 2017).

63 Apart from bulk properties, tillage also affects pore morphology. Tillage forms soil clods, i.e., chunks of
64 intact soil in which the older soil structure is conserved, that are embedded in a loose, broken up soil
65 matrix with isotropic pores and increased meso to macroporosity (Dal Ferro et al., 2014; Kravchenko et
66 al., 2011; Schlüter et al., 2018). Tillage destroys continuous biopores, whereas no-till leads to the buildup
67 of elongated biopores through root growth and earthworm activity that become partially re-filled over
68 time (Lucas et al., 2019; Peth et al., 2008). An indirect effect of tillage on soil structure is the
69 accumulation of soil organic carbon in the first 10cm of the topsoil under no-till (Blanco-Canqui and Ruis,
70 2018; Tebrügge and Düring, 1999), which leads to a higher soil structure stability and in combination
71 with higher antecedent bulk density to a lower susceptibility to soil compaction (Rücknagel et al., 2017).

72 Changes in the pore structure have direct consequences for water retention in mesopores as well as fast
73 water flow and aeration through macropores. The effect of tillage intensity on infiltration capacity and
74 saturated hydraulic conductivity has been intensively studied, but there is no consensus on general
75 trends (Strudley et al., 2008). Preferential flow through the macropore network may (Lipiec et al., 2006;

76 Pagliai et al., 2004) or may not (Kahlon et al., 2013; Vogeler et al., 2009) increase under no-till depending
77 on whether the higher degree of bioturbation and preservation of biopores can compensate for the loss
78 in macroporosity due to soil compaction. Very often, notoriously high spatial and temporal variability
79 disguised trends in hydraulic conductivity caused by tillage intensity (Alletto and Coquet, 2009; Buczko et
80 al., 2006; Jirků et al., 2013; Rienzner and Gandolfi, 2014; Schwen et al., 2011; Strudley et al., 2008).

81 Another reason for mixed results across studies about tillage effects on saturated and near-saturated
82 hydraulic conductivity is uncertainty in the measurement itself (Morbidelli et al., 2017). There are several
83 techniques to conduct infiltration experiments in the field or on undisturbed soil cores at full saturation
84 or low suction such as tension disk infiltrometers (Perroux and White, 1988), hood infiltrometers
85 (Schwärzel and Punzel, 2007) or the Guelph permeameter (Reynolds and Elrick, 1985). Due to the
86 different approaches to bring the infiltrating water in contact with the soil, different strategies to
87 prevent surface sealing and pore clogging, different soil volumes that are probed by the infiltration front
88 or sampling artifacts in soil cores like wall disturbances, differences in derived conductivities of more
89 than one order of magnitude have been reported (Fodor et al., 2011; Reynolds et al., 2000; Schwärzel
90 and Punzel, 2007).

91 Until recently there was no way to disentangle true pore structure effects from deficiencies in the
92 infiltration measurements. With the advent of non-invasive imaging of soil structure with X-ray
93 computed tomography (X-ray CT) and direct simulation of water flow on 3D soil structure images with
94 massively parallel computing (Andrä et al., 2013; Blunt et al., 2013) it should be possible to determine
95 the resistance that the original soil structure imposes on water flow and distinguish it from
96 measurement artifacts like air entrapment and wall effects.

97 X-ray CT analysis of undisturbed soils cores have paved the way to assess soil structure through pore
98 space characterization and to disregard the concept of soil aggregates altogether (Rabot et al., 2018).
99 This quantitative description of soil structure has also been identified as a chance to improve pedo-
100 transfer functions (PTF) for hydraulic conductivity (Van Looy et al., 2017; Vereecken et al., 2010; Zhang
101 and Schaap, 2019), i.e., to amend its prediction based on models with easily available soil properties like
102 texture, bulk density and organic carbon content with structural properties. As we will show, despite
103 having the same texture and higher bulk density no-till soils may have higher saturated conductivity than
104 tilled soils, when macropore flow through large continuous, biopores occurs. Accounting for macropore
105 features in future PTFs requires to (1) identify the most promising structural metrics to predict flow, (2)
106 to initiate large databases in which hydraulic properties and structural properties are stored together
107 and (3) to get a better understanding of the uncertainty that comes with predictions based on structural
108 properties and the uncertainty that comes with the measurement itself. Picking up the recent work of
109 other groups (Koestel et al., 2018; Zhang et al., 2019), this study was our first step into this direction

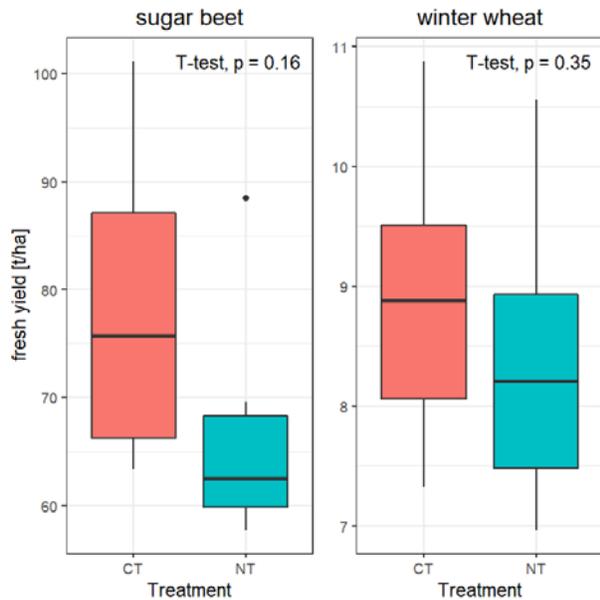
110 The main objective of this study was to investigate tillage effects on macropore structure, saturated and
111 near-saturated conductivity. The study was carried out on a long-term tillage trial (26 years) in Southeast
112 Germany and compared non-tilled with plowed topsoils. Hydraulic measurements were conducted with
113 hood infiltrometers in the field, with tension disc infiltrometers on undisturbed soil cores that were
114 scanned with X-ray CT and with direct simulation of water flow on the resulting macropore structure.
115 Another aim of this study was to explore how well the pore structure attributes derived from X-ray

116 tomography are suited to predict saturated and near-saturated hydraulic conductivity measured with
117 different methods. Our hypotheses were that (i) the predictive power of pore structure attributes should
118 be highest on simulated conductivities, as these are based on exactly the soil core volume and are free of
119 measurement artifacts. (ii) Furthermore, if the set of attributes fully captures the structural properties
120 that govern water flow, then their predictive power should be equally high for both tillage treatments.

121 **2. Material and Methods**

122 **2.1. Field trial description**

123 The long-term field trial is located in Lüttewitz, Germany (51°7'6N, 13°13'43E, 275 m.a.s.l.) and receives
124 a mean annual precipitation of 643 mm with a mean annual temperature of 8.1 °C (Schmidt et al., 2002).
125 The soil type is a Haplic Luvisol (German: Parabraunerde) on loess deposits. The field trial was
126 established in 1992 and is composed of four tillage treatments in large parallel strips between 5.4 and
127 7.8 ha: 1. conventional tillage (CT) with a moldboard plow (up to 30 cm depth), 2. deep mulch tillage, 3.
128 shallow mulch tillage, 4. no-tillage (NT). In this study only the CT and NT treatments are investigated. The
129 three-year crop rotation comprised sugar beet in the first year (*Beta vulgaris*), followed by two years of
130 winter wheat (*Triticum aestivum*). Seedbed preparation on CT before winter wheat and sugar beet was
131 done with a cultivator down to 10 cm. On NT, a shallow seedbed (3-5 cm) cultivation was only done
132 before sugar beet to ensure the establishment of the crop (Koch et al., 2009). Sampling was carried out
133 in spring 2018 in winter wheat (after sugar beet), seven months after the last plowing in the CT
134 treatment. The trial has no replicated plots, but all locations were situated on flat terrain and had very
135 similar silt loam texture (CT - 18% clay, 78% silt, 4% sand; NT - 20% clay, 77% silt, 3% sand). The bulk
136 density measured in 10cm depth was higher in the NT strip (1.53 ± 0.05) as compared to the CT strip
137 (1.40 ± 0.06) and coincide with previously reported values (Jacobs et al., 2015). Organic carbon (C_{org}) and
138 total nitrogen (N) contents in that depth were only slightly higher on the NT strip (C_{org} 1.28 %, N 0.14%)
139 compared to CT (C_{org} 1.21 %, N 0.13%). Across the profile C_{org} and N contents are more evenly distributed
140 on the tilled soil while on NT there is a stratification with an accumulation on the soil surface
141 (Andruschkewitsch et al., 2013).



142

143 **Figure 1: Yield data for sugar beet (n=6) and winter wheat (n=11) in the plots with conventional tillage (CT) and no-tillage**
 144 **(NT). The record comprises all years from 2002 to 2018.**

145 On average, both winter wheat and sugar beet yields were higher on CT compared to NT. From 2002 to
 146 2018 winter wheat yielded 9.1 t ha^{-1} on the tilled plot while the untilled plot yielded 8.6 t ha^{-1} (both 85%
 147 dry matter). For the same time frame, sugar beet yields amounted to 78.3 t ha^{-1} on the CT and 66.7 t ha^{-1}
 148 on the NT plot (taproot fresh matter). For both crops the differences were not significant due to
 149 considerable variations in yield between years. Average yields in the reduced tillage plots ranged in
 150 between NT and CT (data not shown).

151 In the absence of tillage both deep-dwelling (anecic), i.e., *Lumbricus terrestris*, and laterally moving
 152 (endogeic) earthworm species, i.e., *Aporrectodea caliginosa*, *A. rosea* and *Allolobophora chlorotica*, were
 153 more abundant (October 2000: CT – 60, NT – 255, April 2001: CT – 45, NT – 102 Ind. m^{-2}) and had a
 154 higher biomass (October 2000: CT – 30, NT – 225, April 2001: CT – 25, NT – 130 g m^{-2}) compared to CT
 155 (Schmidt et al., 2002). This is in line with observations from other long-term tillage trials in that region
 156 with similar soil texture (Schlüter et al., 2018; Ulrich et al., 2010). This has implications for bioturbation
 157 and consequently soil structure on both plots which will be addressed in this study.

158 Undisturbed soil cores (\varnothing : 10 cm, h: 10 cm) were acquired with a rotating sampling device (Kuka et al.,
 159 2013) (UGT GmbH, Germany) directly underneath the infiltration experiment in a depth of 10-20cm in
 160 the drained soil two days after infiltration. The soil cores were wrapped in air-tight bags to reduce
 161 evaporation and stored at 4°C to reduce biological activity prior to X-ray tomography analysis. Smaller
 162 soil cores (100cm^3) were acquired in the direct vicinity of the infiltration experiments for bulk density
 163 measurements.

164 **2.2.(Near-)Saturated hydraulic conductivity and water-conducting porosity**

165 Thirteen sampling locations for hood infiltrometer (HI) measurements were chosen in each treatment
 166 with a spacing of approx. 50m in between. The HI measurements (IL 2700, UGT GmbH, Germany) were
 167 carried out at pressure heads (h) of 0 and then repeated at -2cm on the same location. At least half a

168 reservoir had to be infiltrated or 10min had to pass to move to the next pressure head. Readings were
169 done every 30 s and steady state was assumed after water level decline in the reservoir did not differ by
170 more than 2 mm for three consecutive steps.

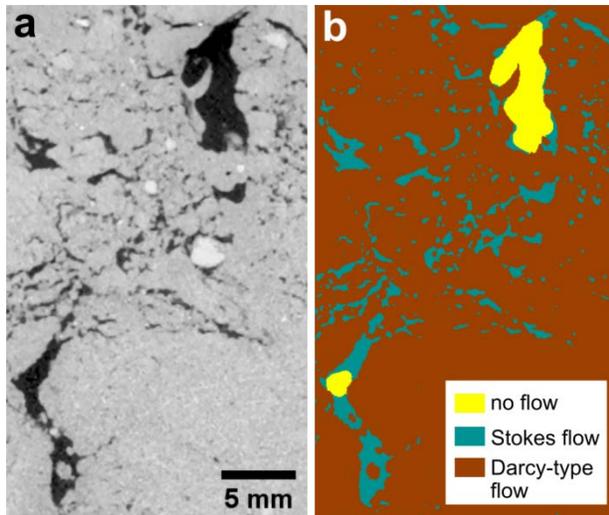
171 Infiltration data was analyzed using the piecewise linear interpolation procedure by Reynolds and Elrick
172 (1991). This procedure is based on the analytical solution for 3D infiltration from a circular source with
173 constant pressure head h by Wooding (1968). Hydraulic conductivity was estimated at the measured h
174 and at their midpoint. As the hood infiltrometer could not always be set to exactly the required h the
175 Gardner (1958) exponential model was used to obtain hydraulic conductivity at $h=0$ and -2 cm (K_s , K_{-2}).

176 Hydraulic conductivity at pressure heads of 0 and -2 cm was measured in this order directly on the soil
177 cores with custom-made tension disc infiltrometers (TI) (Perroux and White, 1988) that exactly fit the
178 inner diameter of the core. The measurements were done after X-ray tomography. The soil cores were
179 saturated from below without vacuum application for 24 hours by placing them in a water bath with a
180 table slightly lower than the core height. This choice against vacuum applications entails more air
181 entrapment, but is closer to the field conditions, where air entrapments are also realistic. The wet soil
182 cores were then placed on a sand bed in which the pressure head was adjusted to the corresponding
183 value of the disc infiltrometer with a hanging water column. The soil surface was filled with a thin sand
184 layer (grain size 0.7-1.2 mm) to improve contact and the bottom of the soil core was supported with a
185 coarse nylon mesh (mesh size 1mm) to prevent soil loss.

186 **2.3.X-ray tomography and image analysis**

187 Soil cores were scanned with X-ray tomography (X-tek XCT 225, Nikon Metrology) at an energy of 180 kV
188 and beam current of 280 μ A and a 1.2 mm Cu filter for beam hardening reduction. 2800 projections were
189 acquired with one frame per projection and an exposure time of 700 ms each. The projections were
190 reconstructed into a 3D tomogram with a filtered back projection algorithm in X-tex CT Pro. The spatial
191 resolution was 60 μ m and the gray scale resolution was 8-bit. The darkest and brightest 0.2% of voxels
192 were set to 0 and 255, respectively, with linear stretching in between.

193 The raw images were filtered with a 3D non-local means filter (Tristán-Vega et al., 2012) using stand-
194 alone software (<https://www.nitrc.org/projects/unlmeans/>). A vertical drift in the mean gray values that
195 is caused by the X-ray CT hardware was corrected with a script written in Quantim (Schlüter et al., 2016).
196 Segmentation into pores and background was carried out with simple thresholding using the average of
197 several histogram-based thresholding methods after outlier removal as implemented in Quantim
198 (Schlüter et al., 2014). The segmented pore space was differentiated into big pores ($d > 1.48$ mm) that
199 are drained at $h=-2$ cm and the remaining macropores that remain water-filled (Figure 2b). This was
200 achieved by employing the 'Local Thickness' method in Fiji/ImageJ, which stores the diameter of the
201 largest sphere that fully fits into the pore space at this voxel location, followed by thresholding at the
202 given pore diameter. This spatial distribution of entrapped air is only hypothetical and based on invoking
203 Young-Laplace law, which typically does not resemble air clusters in wet soil (Pot et al., 2015), as their
204 shape and position would also depend on air continuity, wettability and the wetting history.



205

206 **Figure 2: (a) 2D slice of a X-ray CT scan after non-local means filtering. (b) Processed image after image segmentation and**
 207 **pore diameter thresholding: porous matrix (brown), water-filled pores (blue), air-filled pores (yellow).**

208 Several pore space attributes were computed on the segmented images using Fiji/ImageJ (Schindelin et
 209 al., 2012): 1. Macroporosity or visible porosity larger than $60\mu\text{m}$ (mp) was derived from voxel counting.
 210 2. The critical macroporosity (cmp) was determined as the minimum macroporosity in the direction of
 211 flow, by sectioning the soil core into horizontal layers of ten voxels (0.6 mm). 3. Pore distance histograms
 212 were derived from the 3D Euclidean distance map in soil. That is, the shortest distance to a macropore
 213 voxel is stored in each soil matrix voxel. The average pore distance (dist) is derived from this pore
 214 distance histogram. 4. Pore diameter histograms were derived from the Local Thickness map. The
 215 average pore diameter (apd) is derived from this pore diameter histogram. 5. The critical pore diameter
 216 (cpd) was determined with the SoilJ plugin for Fiji/ImageJ (Koestel, 2018). It corresponds to the
 217 bottleneck in the percolating pore clusters that connect the top and bottom boundaries of the image. 6.
 218 The Γ indicator (conn) is derived from the size distribution of individual pore clusters resulting from
 219 Connected Components labeling in the MorpholibJ plugin of Fiji/ImageJ (Legland et al., 2016). This
 220 connectivity indicator Γ quantifies the connection probability between two randomly chosen pore
 221 voxels. It is one if all pore voxels are connected in one big cluster and approaches zero if the pore space
 222 is very fragmented (Jarvis et al., 2017; Renard and Allard, 2013).

223 This selection of pore space attributes has been carefully curated for this study due to their reported
 224 ability to predict flow based on theoretical considerations, e.g., mp as a term in the Kozeny-Carman
 225 equation (Zhang and Schaap, 2019), cpd as a cornerstone in percolation theory and critical path analysis
 226 (Katz and Thompson, 1986; Koestel et al., 2018), or cmd for being a proxy for the harmonic mean of
 227 permeabilities that can be expected for heterogeneity perpendicular to the flow direction (Renard and
 228 De Marsily, 1997). In addition, several empirical studies have shown that the selected set of pore space
 229 attributes or a subset of it performed better than other image-derived attributes to predict saturated or
 230 near-saturated flow (Koestel et al., 2018; Paradelo et al., 2016; Zhang et al., 2019)

231 **2.4. Direct simulation of saturated hydraulic conductivity**

232 Saturated and near-saturated water flow was modeled by direct simulation (DS) on the segmented X-ray
 233 CT images with a Stokes-Brinkmann solver as implemented in the FlowDict module of Geodict (Revision

234 31172, Math2Market GmbH, Germany). The LIR solver (Linden et al., 2015) with an adaptive finite
235 volume grid was used to calculate the steady-state flow field and derive saturated hydraulic conductivity
236 as well as near-saturated hydraulic conductivity at $h=-2\text{cm}$, for which the largest pores were blocked by
237 air (Figure 2b). The finite volume approach in combination with adaptive grid methods requires
238 significantly less memory than comparable Lattice-Boltzmann methods. In this way it was possible to use
239 the entire, undisturbed part of the soil core at the original resolution ($60\mu\text{m}$) as a model domain ($1530 \times$
240 1530×1450 voxels). The Stokes-Brinkmann equations allow for a coupling between fast, laminar Stokes
241 flow in the segmented pore space and slow Darcy-type flow through the porous soil matrix (Figure 2b).
242 Periodic boundary conditions in flow direction were used including a 2 mm thick redistribution layer at
243 the top and bottom of the model domain. The effective hydraulic conductivity of the soil matrix was set
244 to 8.5 cm/d (permeability 10 mD), a typical value derived from pedo-transfer functions for this texture
245 and a bulk density of 1.65 g/cm^3 (Ad-hoc-AG Boden, 2005; Schaap et al., 2001). This matrix density was
246 estimated by extrapolating the data from image-derived macroporosity and measured bulk density to
247 zero macroporosity. A sensitivity analysis showed that a reduction of this matrix conductivity by an order
248 of magnitude (1 mD) had virtually no effect on effective conductivity of the entire core and an increase
249 by one order of magnitude (100 mD) only increased effective conductivity by less than 5%. This is
250 because a decrease in background conductivity funnels more flow through the macropore system and
251 vice versa.

252 2.5. Statistical analysis

253 The software R, version 3.5.3 (R: The R Project for Statistical Computing) was used for the statistical
254 evaluation of the data. All measured properties were tested for normal distribution using the Shapiro-
255 Wilk test. Macroporosity, critical macroporosity, average pore size, average pore distance, water-
256 conducting porosity, as well as the logarithm of the saturated conductivity of the direct simulation were
257 not normally distributed. A T-test (normally distributed data) or a Mann-Whitney-U-test (non-normally
258 distributed data) was performed to test for significant differences in the mean of both treatments.

259 The correlation of the pore space attributes (independent variable) with the hydraulic conductivities
260 (dependent variable) was carried out with Spearman rank correlation coefficients, since the relationships
261 are not necessarily linear. In addition, a partial least square regression (PLSR) implemented in the *p/s*
262 package (Mevik, 2016) resulted in the percentage of variance in the dependent variable that is explained
263 by the independent variables. Since PLSR assumes normal distributions, the values with metric units
264 (sizes and distances) were transformed using a logarithmic transform and ratios between 0 and 1
265 (porosity, connectivity and critical macroporosity) were transformed with a logistic function. All data
266 ranges were standardized by a z-transform (zero mean and standard deviation of one).

267 Coefficients of determination R^2 and regression lines shown in the figures were generated by the
268 *ggpmisc* package.

269 3. Results

270 3.1. Hydraulic properties

271 Despite the higher bulk density in NT strip as compared to the CT strip the non-tilled soil exhibits a trend
 272 ($p < 0.1$) towards larger saturated hydraulic conductivities when measured with a hood infiltrometer at
 273 the soil surface (Table 1). The difference becomes even more significant ($p < 0.05$) when measured at $h =$
 274 2 cm.

275 The hydraulic conductivities at a given pressure head were substantially lower when measured with
 276 tension disk infiltrometers directly on the soil cores taken from a soil depth of 10-20cm instead HI
 277 measurements at the soil surface. Note that the bulk density was reported to increase with depth from
 278 1.35 g/cm^3 (0-10cm) to 1.41 g/cm^3 (10-20cm) in the CT strip and from 1.44 g/cm^3 (0-10cm) to 1.52 g/cm^3
 279 (10-20cm) in the NT strip (Jacobs et al., 2015). A very conservative estimate of the HI front depth from
 280 the amount of infiltrated water, antecedent water content and piston flow assumption amounts to 19
 281 and 33cm on average for CT and NT, respectively. So the HI measurements should have partially or fully
 282 included most of the soil core volume used for TI. Since the infiltration front in the field is more irregular
 283 it likely reached beyond the sampled depth (10-20cm) also in the CT soil and might have been affected
 284 by the plow pan and undisturbed soil structure underneath it, both of which have a higher bulk density
 285 (CT: 20-30 cm: 1.46 g/cm^3 , 30-45cm: 1.55 g/cm^3 , Jacobs et al. (2015)) than the plow horizon sampled with
 286 TI and therefore exert a higher resistance to flow. Furthermore, the order is reversed between tillage
 287 treatments in the TI data. There is a trend towards lower $\log_{10}K_s$ ($p < 0.1$) and significantly lower
 288 conductivities at $h = -2 \text{ cm}$ ($p < 0.001$) in NT soil cores.

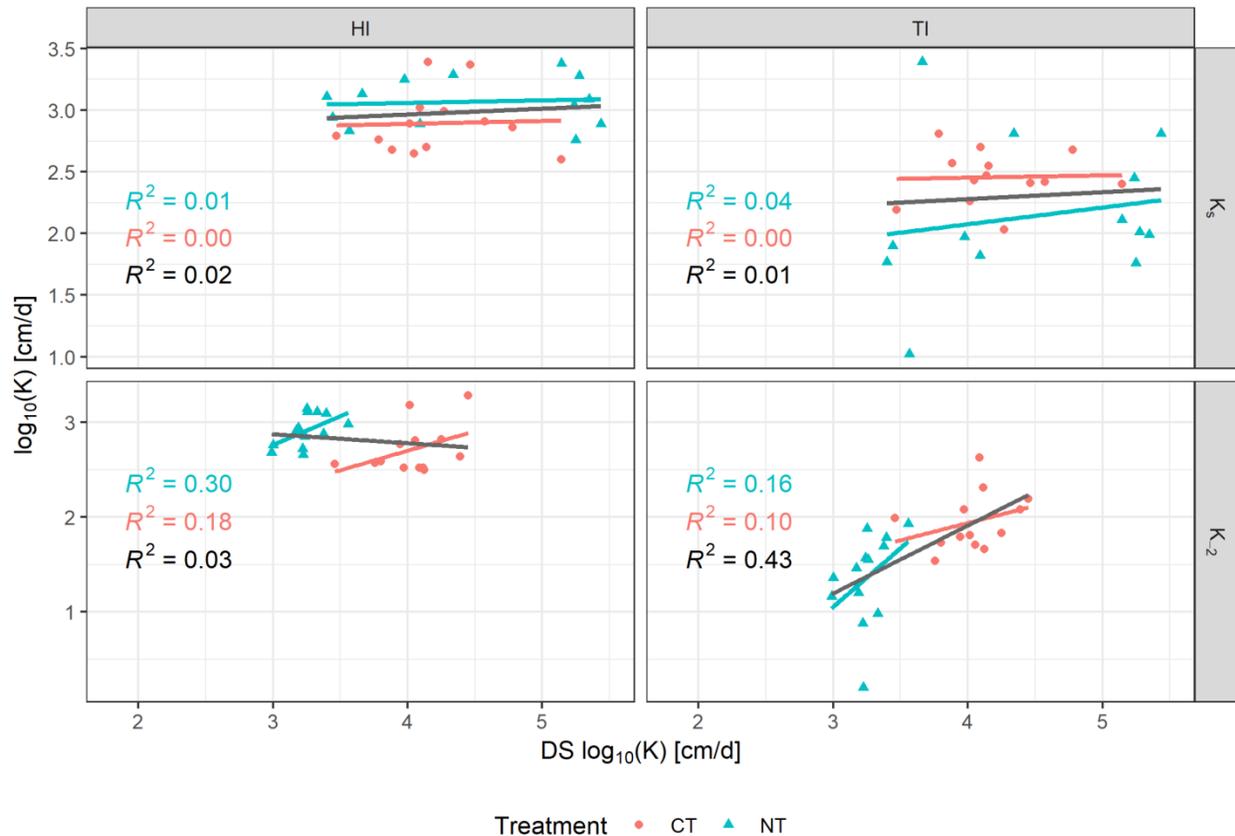
289 The saturated hydraulic conductivity obtained with direct simulation on the segmented X-ray CT image
 290 of the pore space is by far the highest of all methods and on average more than one order of magnitude
 291 larger than those obtained with infiltrometers. There is no significant difference in simulated $\log_{10}(K_s)$
 292 between the tillage treatments. On average near-saturated hydraulic conductivity drops by one order of
 293 magnitude in NT soil cores as compared to K_s , whereas there is hardly any change in CT soil cores. This
 294 causes a significantly lower $\log_{10}(K_{-2})$ in non-tilled soils ($p < 0.05$).

295 **Table 1: Hydraulic conductivities of measured with different methods in the conventional tillage (CT) and no-till (PT) plots**
 296 **(n=13). Test results for significant differences are displayed in the row header (** - $p < 0.01$, * - $p < 0.05$, ° - $p < 0.1$,**
 297 **NS – not significant).**

technique	property	Treatment	Mean	SD
HI - Hood Infiltrometer	$\log_{10}K_s^{\circ}$ [cm d ⁻¹]	CT	2.89	±0.24
		NT	3.07	±0.19
HI - Hood Infiltrometer	$\log_{10}K_{-2}^*$ [cm d ⁻¹]	CT	2.71	±0.25
		NT	2.91	±0.16
TI - Tension Disk Infiltrometer	$\log_{10}K_s^{\circ}$ [cm d ⁻¹]	CT	2.46	±0.22
		NT	2.14	±0.60
TI - Tension Disk Infiltrometer	$\log_{10}K_{-2}^{***}$ [cm d ⁻¹]	CT	1.95	±0.30
		NT	1.36	±0.48
DS - Direct Simulation	$\log_{10}K_s^{NS}$ [cm d ⁻¹]	CT	4.11	±0.44
		NT	4.37	±0.82
DS - Direct Simulation	$\log_{10}K_{-2}^*$ [cm d ⁻¹]	CT	4.03	±0.26
		NT	3.25	±0.15

299 The correlation between all three saturated hydraulic conductivities on a sample level is very low (Figure
 300 3), with $R^2 < 0.05$ for all combinations of methods and tillage treatments. A pertinent pattern in saturated
 301 hydraulic conductivity derived from direct simulation is that NT cores are grouped into small values
 302 ($\log_{10}K_s < 4.2$) and large values ($\log_{10}K_s > 5.0$) presumably depending on whether there exists are large
 303 continuous biopore in the direction of flow, whereas all other combinations of methods and tillage
 304 treatment evoke normality in the residuals around the means.

305 The correlations between the three techniques are somewhat higher ($0.1 < R^2 < 0.3$) for near-saturated
 306 hydraulic conductivities of individual tillage treatments (Figure 2). Pooling the treatments leads to a
 307 higher coefficient of determination ($R^2 = 0.43$) between DS and TI, but not between DS and HI ($R^2 = 0.03$).

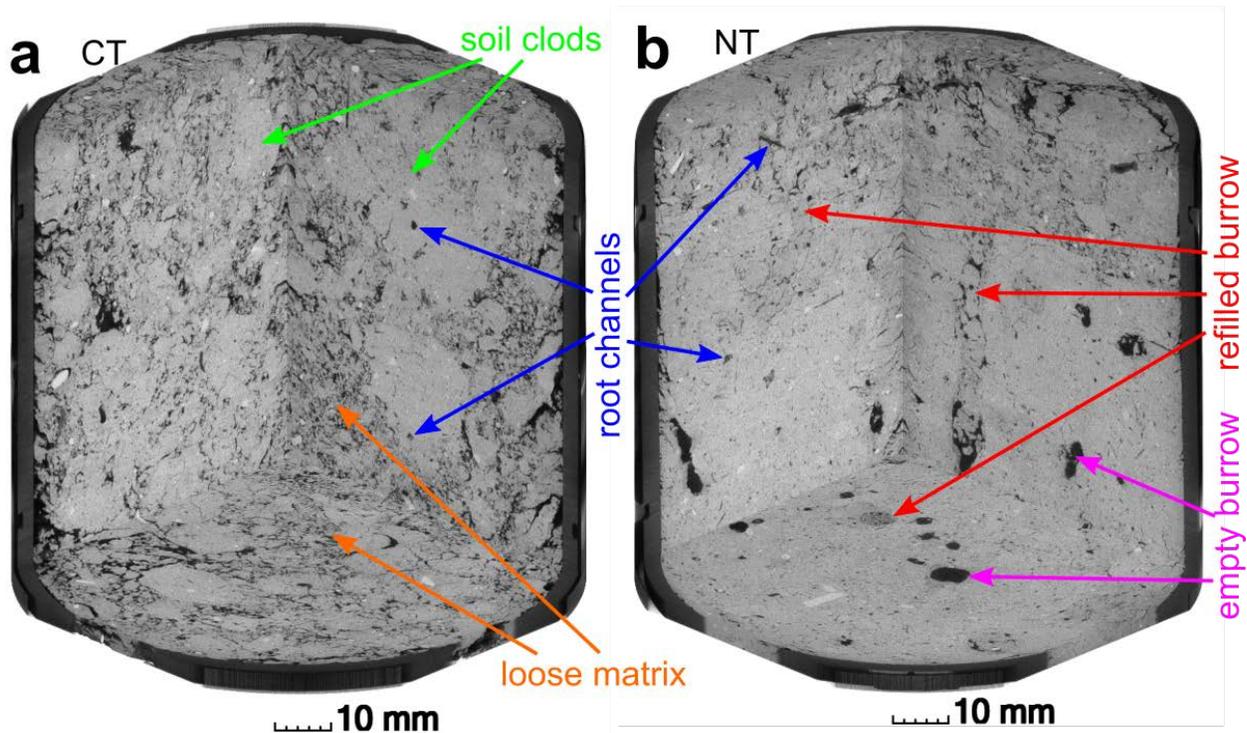


308
 309 **Figure 3: Log-transformed saturated hydraulic conductivities (K_s) and near-saturated hydraulic conductivities (K_2) derived**
 310 **from hood infiltrometers in the field (HI), tension disc infiltrometers on intact soil samples (TI) and direct flow simulations on**
 311 **the 3D pore structure (DS). Note the different scale for the three measurement types.**

3.2. Visual assessment

313 A typical sample with pore structure properties close to the average of each tillage treatment is
 314 visualized in Figure 4. The effect of plowing or the lack thereof is clearly visible in the X-ray CT images.
 315 Plowing leads to a loose matrix with embedded clods, in which the structure prior to plowing is
 316 conserved (Figure 3a). Root channels are clearly visible as dark spots in dense clods but also exist within
 317 the loose matrix. The pore structure in the non-tilled soil is clearly different (Figure 3b). The loose soil
 318 matrix is only present in earthworm burrows that are partially refilled with earthworm cast. The top of

319 the core seems to have a higher volume fraction of loose soil matrix (10-13cm depth in the profile)
320 perhaps due to soil structure disturbance during sugar beet harvest. The rest of the soil is mainly
321 composed of a dense matrix with local bulk density that is likely to be even higher than the average bulk
322 density of 1.53g/cm³.



323
324 **Figure 4: X-ray tomogram cut along three principal plans for one example of (a) plowed topsoil and (b) no-till soil from a**
325 **depth of 10-20cm each. Salient features are annotated.**

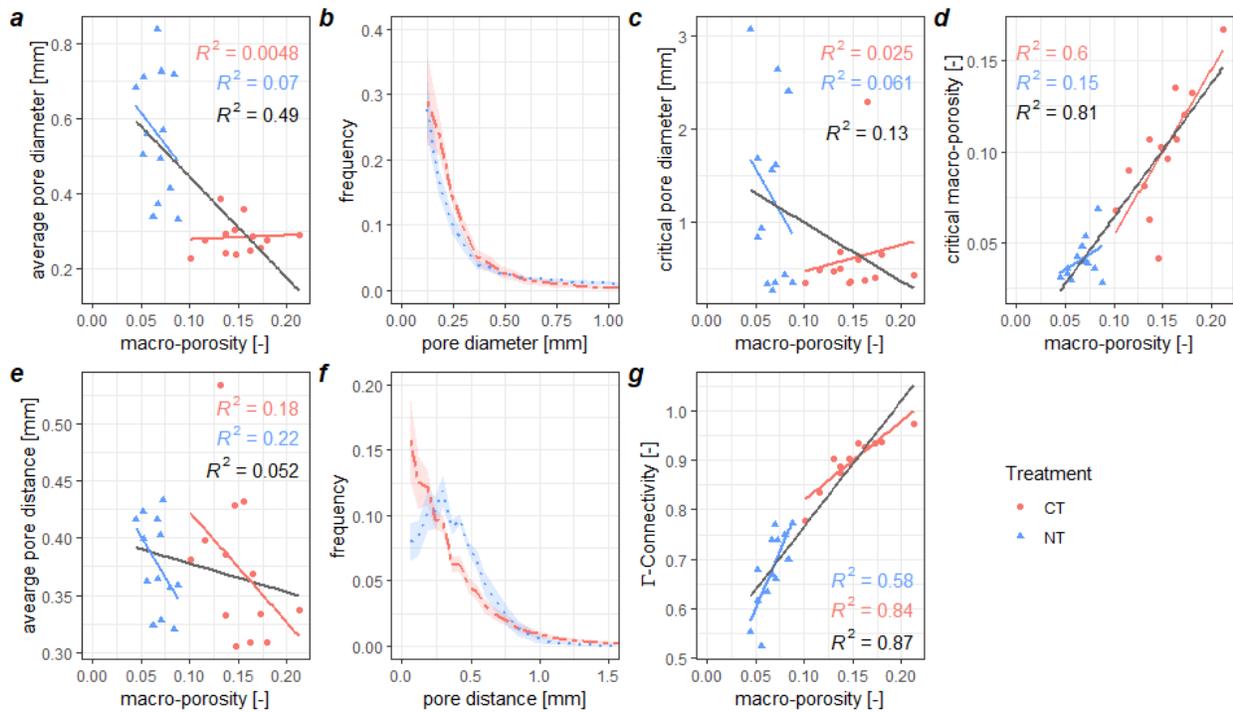
326 3.3. Pore structure attributes

327 The visual assessment of X-ray tomograms is corroborated by image analysis results (Table 2). The
328 macroporosity in the NT cores is significantly smaller ($p < 0.001$), which is in line with the higher bulk
329 density. This lower macroporosity also entails a lower critical macroporosity in the direction of flow
330 ($p < 0.001$) and leads to a significantly lower connection probability ($p < 0.001$). Interestingly, the average
331 pore diameter is larger ($p < 0.001$) in the NT cores, because of a higher contribution from large biopores
332 to total macroporosity, whereas in CT cores the frequency of biopores, cracks and pores in the loose soil
333 matrix with diameters $< 0.5\text{mm}$ is higher (Figure 5b). This is also reflected in a higher critical pore
334 diameter in NT cores ($p < 0.05$). Surprisingly, the average pore distance is the same in both structures
335 despite the different visual appearance and the higher macroporosity in CT soil. Short distances
336 $< 0.25\text{mm}$ are more frequent in the CT soil due to larger pore surface area contributed mainly by the
337 loose soil matrix (Figure 5b). But this is compensated by a higher frequency of large pore distances
338 $> 0.75\text{mm}$ in the CT soil which are located in dense clods, so that on average the bulk pore distance is
339 comparable to NT soil with a more even spacing of biopores in an otherwise dense matrix.

340 **Table 2: Image-derived pore structure attributes from the conventional tillage (CT) and no-till (PT) plots (n=13). Test results**
 341 **for significant differences are displayed in the column header (** - p<0.01, * - p<0.05, ° p<0.1, NS – not**
 342 **significant).**

Treatment	macroporosity ^{***} [-]		critical macroporosity ^{***} [-]		Γ connectivity ^{***} [-]		average pore diameter ^{***} [mm]		critical pore diameter [*] [mm]		average pore distance ^{NS} [mm]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CT	0.15	±0.03	0.10	±0.03	0.90	±0.05	0.28	±0.04	0.61	±0.50	0.37	±0.06
NT	0.07	±0.01	0.04	±0.01	0.68	±0.08	0.56	±0.16	1.26	±0.93	0.38	±0.04

343 More trends and dependencies among pore structure attributes are revealed by analyzing trends in the
 344 scatter and correlation between attributes (Figure 5). There is no correlation between average pore size
 345 and macroporosity within a treatment. This low correlation suggests that both properties carry
 346 complementary information that in combination may help to explain measured K_s and K_2 values better.
 347 Pooling the data may lead to the impression that an increase in macroporosity leads to a decrease in
 348 average pore diameter (Figure 5a). This is because the gain in macroporosity in CT samples is mainly
 349 caused by an increased volume fraction of pores <0.25mm in the loose soil matrix due to plowing
 350 (Figure 5b). The very high correlation between connectivity and macroporosity goes to show that both
 351 attributes carry redundant information (Figure 5c). The slope is steeper for NT samples as their
 352 macroporosities are in the critical range for percolation, whereas CT samples have a well-connected
 353 macropore space leading to connection probabilities closer to the theoretical limit of one and therefore
 354 generally to a smaller increase in connectivity with increasing macroporosity. The critical macroporosity
 355 also exhibits a high correlation with macroporosity, in particular for CT soil cores in which individual
 356 layers are fairly representative for the entire core, but less so for NT soil cores in which critical
 357 macroporosities are typically reached in very dense layers at the bottom of the cores. The average pore
 358 distance decreases with increasing macroporosity in a fairly consistent way for each tillage treatment
 359 (Figure 5b) despite the higher macroporosity in CT soil, but the correlation is generally lower than that
 360 observed for connectivity and macroporosity. The critical pore diameter is not correlated with
 361 macroporosity in either of the treatments, since the volume fraction of macropores has little effect on
 362 the bottleneck diameter through the percolating pore cluster.



363

364 **Figure 5: Relationship between different pore structure attributes: (a) average pore size as function macropositivity, based on**
 365 **(b) the pore size histogram. (c) connection probability Γ as a function of macropositivity. (d) average pore distance as a**
 366 **function of macropositivity, based on (e) the pore distance histogram. (f) critical pore diameter as a function of macropositivity.**

367 3.4. Relationship between hydraulic conductivity and pore space attributes

368 The Spearman rank correlation coefficients between image-derived pore space attributes and (near-)
 369 saturated hydraulic conductivity obtained with different techniques (Table 3) exhibit some highly
 370 significant correlations, yet with a fairly inconsistent pattern. High correlations may vanish when
 371 switching from one tillage treatment to the other (or pooling the data), from saturated to near-saturated
 372 hydraulic conductivity or from one technique to the other. Yet, some general deductions may seem valid.
 373 First, among all three techniques K -values obtained with DS seem to correlate best with pore space
 374 attributes. Second, for DS the most important pore space attribute for K_s values is the critical pore
 375 diameter, in particular for NT cores, in which earthworm burrows are the major pathway for flow. That
 376 changes for K_2 values, when these channels are blocked by air (Figure 2b) and the remaining macropore
 377 network conducts the flow, which is best described by macropositivity and pore connectivity. Third, for all
 378 three techniques K_2 values correlate better with pore space attributes of pooled data than individual
 379 tillage treatments. That is, they are more sensitive to the very different flow patterns between CT and NT
 380 cores, than to the variability of hydraulic conductivity within a tillage treatment.

381 **Table 3: Spearman rank correlation coefficients between hydraulic conductivities obtained with different techniques at**
 382 **different pressure heads and pore space attributes derived from X-ray CT images (** - $p < 0.01$, * - $p < 0.05$,**
 383 **$p < 0.1$).**

property	technique	treatment	mp [-]	cmp [-]	conn [-]	apd [mm]	cpd [mm]	dist [mm]
log10 K_s	HI	CT	0.24	0.05	0.52 °	0.61 *	0.41	0.46
		NT	0.24	0.03	0.57 *	0	-0.04	0.21

	CT+NT	-0.25	-0.28	-0.11	0.55 **	0.2	0.37 °
	CT	0	0.14	-0.05	0.02	0.09	0.09
TI	NT	0.29	-0.09	0.39	0.25	0.17	0.05
	CT+NT	0.38 °	0.26	0.39 *	-0.29	0.02	0.01
	CT	0.63 *	0.3	0.62 *	0.35	0.19	-0.13
DS	NT	0.03	0.24	-0.23	0.84 ***	0.89 ***	0.11
	CT+NT	-0.03	0.05	-0.08	0.48 *	0.78 ***	0.1
	CT	0.08	0	0.35	0.51 °	0.43	0.41
HI	NT	0.26	-0.04	0.61 *	0.14	0.14	0.31
	CT+NT	-0.37 °	-0.39 *	-0.22	0.62 ***	0.24	0.43 *
	CT	0.25	-0.19	0.21	0.34	0.03	0.21
log ₁₀ K ₂	TI	0.16	-0.3	0.57 *	-0.3	-0.37	-0.06
	CT+NT	0.65 ***	0.39 *	0.72 ***	-0.53 **	-0.29	0.04
	CT	0.78 **	0.48 °	0.90 ***	0.51 °	0.18	-0.04
DS	NT	0.58 *	-0.07 °	0.90 ***	-0.52 °	-0.49 °	0.08
	CT+NT	0.92 ***	0.72 ***	0.97 ***	-0.70 ***	-0.32	-0.08

384

385 A general shortcoming of Spearman rank correlations is that they do not indicate the type of relationship
 386 between a pore metric and conductivity, i.e., whether it is linear or non-linear. Therefore, it is not
 387 possible to assess, whether one is a good predictor for the other and therefore a suitable candidate for
 388 deriving pedo-transfer functions.

389 To do so, requires a partial least regression between pore space attributes and hydraulic conductivities.
 390 In Table 4, these results are reported as percentage of variance in the dependent variable (K values) that
 391 is explained by the independent variables (pore space attributes). The percentage of explained variance
 392 in log₁₀(K_s) measured with hood infiltrometers is higher for CT soil (72.9%) than for NT soil (43.4%) (Table
 393 2). The explained variability in log₁₀(K_s) for NT cores is lower either because the core volume (700cm³) is
 394 less representative for the pore structure that is encountered by the infiltration front or because the
 395 investigated attributes are less adequate for predicting flow in this very different structure. The
 396 explained variance is decreased further by pooling all infiltration experiments. Individual simple
 397 regressions show that the attribute with the highest predictive power differs among treatments. In CT
 398 cores it is the average pore diameter (62.6%) followed by average pore distance (34.7%) and pore
 399 connectivity (8.7%). It is safe to assume that saturated flow will mainly occur through the loose matrix
 400 produced by plowing. These attributes best describe the channel width within the loose matrix, the
 401 volume fraction of the loose matrix (i.e., small pore distances are caused by many small soil fragments in
 402 the loose matrix) and the connectivity of pores through the loose matrix, respectively. In NT cores the
 403 variability in log₁₀(K_s) is best described by pore connectivity (34.9%) followed by macroporosity (10%) and
 404 average pore distance (6.6%). In NT samples large biopores are supposed to contribute more to
 405 saturated flow. In presence of a dense soil matrix, the connectivity of these channels becomes more
 406 important for water flow. Especially since the observed connectivities are in the critical range between
 407 0.4 and 0.8, whereas in the CT cores macropore structures are very well connected anyway ($\Gamma > 0.8$).
 408 The fact that the macroporosity is in a critical range for percolation in NT cores, but not in CT cores, also

409 explains the higher predictive power of macroporosity on $\log_{10}(K_s)$ for NT. The critical pore diameter does
 410 not carry predictive power in either of the treatments, perhaps because a large 3D infiltration front in
 411 the field is not constrained by a single pore bottleneck and if so, it might be located outside analyzed soil
 412 core.

413 **Table 4: Partial least square analysis resulting in the percentage of variance [%] in $\log_{10}(K_s)$ and $\log_{10}(K_2)$ that can be**
 414 **explained with individual pore metrics or all jointly. The color code scales from low (white) to high (green) predictive power.**

property	tech- nique	treat- ment	mp [-]	cmp [-]	conn [-]	apd [mm]	cpd [mm]	dist [mm]	joint
$\log_{10}(K_s)$ [cm d ⁻¹]	HI	CT	2.2	0.5	8.7	62.6	3.5	34.7	72.9
		NT	11.0	0.1	33.3	0.0	0.1	5.9	43.4
		CT+NT	6.2	7.6	2.0	20.5	4.8	21.1	40.3
	TI	CT	0.0	0.8	0.0	0.1	3.0	1.6	34.3
		NT	3.7	7.2	8.5	0.3	1.0	0.0	65.7
		CT+NT	13.3	4.8	13.5	6.1	0.1	0.0	21.1
	DS	CT	34.2	11.1	33.7	3.6	11.4	4.6	48.4
		NT	3.6	10.9	4.0	78.0	91.4	4.2	94.8
		CT+NT	2.1	0.0	1.1	34.7	66.1	0.1	77.6
$\log_{10}(K_2)$ [cm d ⁻¹]	HI	CT	0.5	0.0	4.4	60.0	0.2	32.1	74.6
		NT	10.5	0.3	39.9	0.3	0.7	13.3	58.2
		CT+NT	10.3	12.4	4.5	25.8	4.4	23.4	46.6
	TI	CT	6.2	3.6	6.6	4.8	27.1	2.1	67.7
		NT	1.4	14.3	12.0	0.3	2.0	1.5	69.7
		CT+NT	36.9	14.4	40.4	23.7	4.2	0.3	54.4
	DS	CT	72.3	16.7	80.0	29.3	4.0	0.3	95.0
		NT	55.1	0.3	82.4	27.1	27.1	0.1	96.0
		CT+NT	91.7	63.8	95.0	51.9	15.4	0.6	96.5

415 The explained variance in $\log_{10}(K_s)$ measured by TI is lower for CT cores (34.3%), but higher for NT cores
 416 (65.7%) as compared to HI measurements when all pore metrics are considered jointly (Table 2). The
 417 explained variance by simple regressions is very low for both tillage treatments, suggesting that the
 418 interaction between these pore metrics contributes a large share to the explained variance in the joint
 419 PLSR.

420 The predictive power of pore metrics on $\log_{10}(K_s)$ simulated with a Stokes-Brinkmann solver directly on
 421 the 3D pore structure is again very dependent on the tillage treatment (Table 4). For non-tilled soils the
 422 predicted variance by all pore space attributes combined amounts to a formidable value of 94.8%, which
 423 is almost exclusively based on the critical pore diameter (91.4%). Evidently, water flow in this structure
 424 depends mainly on the presence of earthworm burrows and is constrained by the bottleneck along those
 425 channels. For tilled soils the explained variance by all pore space attributes combined reaches only 48.4%
 426 and is mainly contributed by macroporosity (34.8%) and as consequence of their high correlation also
 427 pore connectivity, whereas the critical pore diameter is less relevant for water flow (11.4%). This again
 428 supports the idea that the volume fraction of the loose soil matrix is constraining $\log_{10}(K_s)$, which is best
 429 captured by bulk macroporosity.

430 The percentage of explained variance in near-saturated hydraulic conductivities at $h=-2\text{cm}$ ($\log_{10}(K_2)$) by
 431 considering all pore metrics jointly is higher than that of saturated hydraulic conductivity ($\log_{10}(K_s)$) for all
 432 measurement techniques and tillage treatments (Table 4). The overall trends are similar to those of the
 433 Spearman rank correlation coefficients (Table 3). That is, macroporosity and connectivity replace critical

434 pore diameter as the pore metric with highest predictive power on simulated hydraulic conductivity (DS).
435 For HI and TI measurements the general pattern of which pore metric has the highest predictive power
436 on $\log_{10}(K_2)$ for a given tillage treatment is identical to that of $\log_{10}(K_s)$.

437 4. Discussions

438 4.1. Predicting saturated hydraulic conductivity

439 Our findings support the consensus in soil hydrology that saturated hydraulic conductivity is difficult to
440 measure, exhibits a notoriously high spatial variability and is therefore afflicted with a high uncertainty
441 (Fodor et al., 2011; Reynolds et al., 2000; Rienzner and Gandolfi, 2014). For all measurements combined
442 the saturated hydraulic conductivity measured with hood infiltrmeters (950 cm/d) was roughly five
443 times higher (Table 1) than measured with tension disc infiltrmeters (200 cm/d). This discrepancy
444 between K_s values obtained with hood and tension disc infiltrmeters is in a comparable range with
445 previous studies (Matula et al., 2015; Schwärzel and Punzel, 2007) and is mainly ascribed to a better
446 hydraulic contact of the hood compared to the tension infiltrmeter (Matula et al., 2015) and
447 disturbances of the soil surface while preparing it for TI measurements. Further, fine particles of the
448 contact material may lead to clogging of pores (Schwärzel and Punzel, 2007). Moreover, hydraulic
449 measurements are known to show hysteretic effects (Clothier and Smettem, 1990) that could have been
450 invoked by saturating the soil cores prior tension disc infiltration whereas HI measurements were
451 conducted directly on field-moist soil. The lack of vacuum when saturating the sample prior to TI
452 measurements could have led to substantial air entrapment. Also, the cores might have been partially
453 drained when quickly moving them from the water bath to the sand bed and this invading air was then
454 additionally trapped during infiltration. Furthermore, we observed slaking and compaction directly
455 underneath the disc infiltrmeter. So the measured conductivities might have been more affected by the
456 pore structure of the first mm than by the entire column and macropores underneath might have
457 become disconnected and stayed inactive (Allaire-Leung et al., 2000; Sammartino et al., 2015). In
458 addition, the contact area of the HI (483 cm²) was larger than the TI (50cm²), averaged across more
459 vertical heterogeneity and might have sampled the macropore system more representatively. This may
460 also explain why NT cores had a higher K_s and K_2 than CT cores when measured with HI, as preferential
461 flow in earthworm burrows contributed more to overall flow and the CT cores were partially affected by
462 the plow pan, whereas the order between tillage treatments was reversed in the TI data, as these large
463 biopores are disrupted by sampling or just not sampled representatively and the effect of the plow pan
464 vanished in the extracted CT cores.

465 Due to uncertain nature of saturated hydraulic conductivity it has been suggested to put more emphasis
466 on measuring near-saturated hydraulic conductivity and e.g., use K_2 as a hinging point to constrain the
467 Mualem model of unsaturated conductivity (Ippisch et al., 2006; Schaap and van Genuchten, 2006). This
468 is supported by our findings (Table 1) as the trends ($p < 0.1$) between both tillage treatments turned into
469 significant differences (HI, $p < 0.05$) and highly significant differences (TI, $p < 0.001$) when considering
470 $\log_{10}(K_2)$ instead of $\log_{10}(K_s)$. Likewise, a non-significant difference in $\log_{10}(K_s)$ turned into significantly
471 higher $\log_{10}(K_2)$ for CT soil for direct simulations. Finally, the correlation between the three different
472 measurement techniques, though still quite poor ($R^2 < 0.5$), also improved when switching from $\log_{10}(K_s)$

473 to $\log_{10}(K_{-2})$ as well as the Spearman rank correlation and partial least square regression between
474 hydraulic conductivity and pore space attributes.

475 The predicted K_s values derived from direct simulation of saturated water flow on the 3D pore structure
476 allow for an assessment of measurement uncertainties that are usually disguised by bulk measurements.
477 For all measurements combined simulated K_s values are much higher (17400 cm/d) than measured K_s
478 values for both tillage treatments. With a few exceptions (Di Prima et al., 2018) such high values are
479 rarely reported for any kind of infiltrometer. This goes to show that some of the assumption made in the
480 direct simulations of macropore flow under ponded conditions, like complete saturation and perfect
481 wettability are quite unrealistic (Jarvis, 2007). The two order of magnitude discrepancy to tension disc
482 infiltrometer measurements could in addition have been caused by clogging of pores with contact sand
483 and structural deformation of soil structure caused by the TI measurement (Koestel et al., 2018) that all
484 impose a substantial resistance to water flow. The discrepancy to hood infiltrometer measurement is
485 structure-dependent and can be partly ascribed to the vastly different soil volumes that act as a flow
486 domain in DS and HI. The grouping of NT samples into highly conductive and less conductive samples
487 caused by individual biopores in the direct simulation data vanishes in the hood infiltrometer data as a
488 large volume captures the elongated biopores and the bottlenecks that restrict flow more
489 representatively. The absolute values in simulated (DS) and measured (HI) conductivity are similar for
490 less conductive NT samples, suggesting that the small, short-ranged flow paths are representatively
491 captured by a 700cm³ core in these dense soil samples. Likewise, the K_{-2} values in NT cores were similar
492 with both techniques (HI: $\log_{10}K_{-2}=2.91$, DS: $\log_{10}K_{-2}=3.25$; Table 1), as large biopores are blocked by air at
493 $h=-2$ cm. Finally, also hood infiltrometer measurements might be afflicted by pore clogging, air
494 entrapment and soil slaking to some extent.

495 Even though the Spearman rank correlation analysis occasionally showed very good agreement between
496 pore space attributes and hydraulic conductivities, the partial least square regression analysis revealed
497 that there is little hope in predicting saturated or near-saturated hydraulic conductivity with a universal
498 pedo-transfer function based on a combination of pore structure attributes. This does not mean that the
499 status quo of not considering image-derived macropore features in pedo-transfer functions for K_s
500 estimates at all (Araya and Ghezzehei, 2019; Carsel and Parrish, 1988; Schaap et al., 2001; Vereecken et
501 al., 2010; Wösten et al., 2001), would be the better option. For instance, K_s predictions using only
502 average texture and bulk density data would have led to a vast underestimation for both tillage
503 treatments (CT: 17 cm/d, NT: 8 cm/d; estimated with Rosetta Lite as implemented in Hydrus 1D). It is
504 frequently observed that these PTF estimates of hydraulic conductivity tend to underestimate measured
505 values in the wet range (Vereecken et al., 2010). More recent approaches to identify key factors
506 controlling K_s and K_{-10} in the field have considered additional input parameters beyond texture, bulk
507 density and soil organic carbon, such as land use, season, annual precipitation and temperature as well
508 as experimental conditions like sequence of applied suctions, disk diameter and K estimation method
509 (Jarvis et al., 2013; Jorda et al., 2015). The most important predictors were annual precipitation and
510 temperature for K_{-10} and land use and bulk density for K_s (Jorda et al., 2015) most likely through their
511 impact on soil structure which is the actual controlling factor of hydraulic conductivity but hard to cast in
512 quantitative terms and rarely reported for field studies in a standardized way to be used in large
513 databases.

514 Here, pore metrics derived from X-ray CT data can contribute a lot to improve PTFs for saturated and
515 near-saturated hydraulic conductivity. But the outcome of our PLSR analysis showed that it is unclear on
516 which pore metric such an extended pedo-transfer function should be based as this changes dramatically
517 between tillage treatments and measurement techniques. The critical pore diameter had an excellent
518 predictive power on simulated $\log_{10}(K_s)$ (explained 91.4% of the observed variability), but only for NT
519 samples in completely saturated soil where the bottleneck in large biopores really imposed the decisive
520 resistance to flow. This confirms recent findings by Koestel et al. (2018) based on infiltration experiments
521 and X-ray CT analysis for a broad selection (n=95) of Norwegian soils that also ascribed the highest
522 predictive power on critical pore diameter. However, in plowed CT soil the predictive power of the
523 critical pore diameter on simulated $\log_{10}(K_s)$ was much lower (11.4%). This change in predictive power
524 between biopore-dominated and matrix-dominated flow confirms recent findings by Zhang et al. (2019).
525 As pointed out by Koestel et al. (2018), the suitability of the critical pore diameter in predicting flow is
526 based on the assumption of a broad distribution of local hydraulic conductivities, which is apparently not
527 justified in more homogenous, tilled soils. In CT soil even the combination of all pore structure attributes
528 left more than half of the observed variability in simulated $\log_{10}(K_s)$ unexplained even though the
529 structure analysis and flow simulation was based on the same volume. It is unlikely that another pore
530 structure metric unaddressed in this study could substantially improve the predictive power, since very
531 often shot-gun approaches that favor a large number of structure parameters over a selected number of
532 targeted, complementary metrics have shown that a large part of them is highly correlated (Larsbo et al.,
533 2014; Müller et al., 2018; Smet et al., 2018), often necessarily so by direct dependencies, and can
534 therefore hardly improve conductivity predictions. The selection of pore space attributes used in our
535 study targeted already those metrics that were identified as the most promising to predict water flow in
536 previous studies (Koestel et al., 2018; Paradelo et al., 2016; Schlüter et al., 2018; Zhang et al., 2019). One
537 way to improve predictions by pore structure attributes could be to divide the domain into several
538 sections in the direction of flow and take the harmonic mean of section averages as predictors of
539 conductivity (Renard and De Marsily, 1997; Wen and Gómez-Hernández, 1996) or only evaluate the pore
540 metrics in the limiting layer (Paradelo et al., 2016; Zhang et al., 2019) to better account for layers with a
541 particularly high flow resistance. Note that this is already partly implemented in this study by accounting
542 for the critical macroporosity in the direction of flow and that this extension would maintain the
543 excellent prediction of conductivity by the critical pore diameter for NT soil cores. Likewise, the
544 assumption of a constant matrix conductivity through unresolved pores for the Stokes-Brinkmann solver
545 might be too strong and could be replaced by a variable matrix conductivity that is coupled to the
546 grayscale in the X-ray CT data (Kang et al., 2019), though our sensitivity analysis showed that the effect
547 on effective conductivity of the core is small. However, it is debatable whether these extensions are
548 warranted since a much larger fraction of unaccounted variability seems to be contributed by
549 deficiencies in the conductivity measurements like air-entrapment, imperfect contact, soil deformation
550 by the measurement or different measurement volumes (Koestel et al., 2018).

551 In summary, these findings confirm previous recommendations (Zhang and Schaap, 2019) that (1) the
552 development of soil structure-based pedo-transfer functions for hydraulic conductivity might benefit
553 from replacing K_s with near-saturated hydraulic conductivity like K_2 as the uncertainty associated with
554 the measurement typically goes down. However, this will also change the order of pore space attributes
555 with the highest predictive power as the largest pores will be blocked by air. (2) When setting up large

556 databases that combine image-derived structural information with measured hydraulic properties, only
557 data with consistent measurement protocols should be incorporated or at least all reported
558 measurement data should be flagged with meta-information on the measurement technique so that
559 data selection can be carried out accordingly prior to training and validation of pedo-transfer functions.

560 **4.2. Ecological relevance of tillage**

561 The increased biopore formation rate through larger earthworm abundance and the better biopore
562 continuity through the lack of plowing caused a trend ($p < 0.1$) towards higher saturated hydraulic
563 conductivities in the NT strip that was even more significant ($p < 0.05$) for near-saturated hydraulic
564 conductivity at the time of sampling, when measured in the field with hood infiltrometers. However,
565 differences in K_s between both tillage treatments vanished when directly simulated on the three-
566 dimensional pore structure and even changed order when measured with tension disc infiltrometers.
567 Furthermore, repeated hood infiltrometer measurements at this site indicate that when measured over
568 several growing seasons (five occasions with $n=5$ per occasion and treatment) on average the differences
569 in K_s between CT (750 cm/d) and NT (492 cm/d) are not significant (unpublished data) and often depend
570 on the time of measurement during a cropping season. K_s values vary considerably over time in the CT
571 plot due to tillage and subsequent soil settling, whereas they are more stable over time in the NT plot.

572 The success of a conversion from conventional tillage to no-till is typically evaluated by its effect on off-
573 site and on-site ecosystem services, of which the most important to farmers is usually crop production
574 but may also include carbon sequestration and resilience to soil degradation. A detrimental effect of no-
575 till for crop production may occur when air capacity falls below a critical value for root penetration and
576 soil aeration due to the lack of soil loosening through plowing. Bulk density in the no-till plot increased to
577 1.53 g/cm^3 ; a value that is around the critical value (1.55 g/cm^3) for root growth restriction in silt loam
578 (Kaufmann et al., 2010). The critical air capacity, i.e., air content at field capacity, for soil aeration is
579 assumed to be 5% (Lebert et al., 2004) to 8-10% (Reichert et al., 2009; Werner and Paul, 1999), which is
580 in the range of macroporosity of the NT soil cores (7%, Table 2). Note that the voxel resolution ($60 \mu\text{m}$)
581 roughly corresponds to the pore diameter with an air entry pressure at field capacity ($pF 1.8$) and can
582 therefore be used as a proxy for air capacity (Schlüter et al., 2018). All measured K_s values in the NT strip
583 seem to be uncritical for crop production as they exceeded the limiting value for ponding estimated at 10
584 cm/d (Werner and Paul, 1999), and ponding might not be critical at this site anyway for its terrain and
585 moderate annual precipitation. Direct drilling as practiced on this site has been shown to result in
586 decreasing yields of both sugar beet and winter wheat (Figure 1 and Jacobs et al. (2015)). Winter wheat
587 may still be produced profitably under such a system (Dieckmann, 2008) as the reduction in yield is
588 compensated by the reduced costs for machinery and labor while at the same time the increase in costs
589 for pest management is only marginal (personal communication with the farmer and Rico Rühl,
590 Südzucker). Soil loosening may be warranted for when growing sugar beet (Koch et al., 2009) in order to
591 achieve more favorable rootability, aeration and pest reduction. In fact, no-till poses an economic
592 disadvantage for sugar beet at this site as the yield reduction and increased costs for pest control are
593 more substantial as compared to winter wheat and cannot be compensated by the reduced costs for
594 tillage (personal communication with the farmer and Rico Rühl, Südzucker).

595 **5. Conclusions**

596 Though a non-replicated trial should be interpreted with caution when drawing general conclusion about
597 the effect of tillage treatments on soil functions, our dataset is useful in demonstrating how the lack of
598 plowing changes morphological features of the macropore network and how this affects (near-)saturated
599 hydraulic conductivity. The increase in K_s and K_2 caused by a higher abundance of large biopores due to
600 higher earthworm abundance and their preserved continuity in the absence of plowing under no-till was
601 only detected with hood infiltrometer measurements in the field but absent in direct flow simulation on
602 the three-dimensional pore structure of undisturbed soil cores and even reversed in tension disk
603 infiltrometer measurements on those soil cores. Each of the three methods resulted in vastly different
604 average saturated hydraulic conductivity (two orders of magnitude) which is ascribed to different
605 averaging volumes as well as various measurement deficiencies such as poor contact, air entrapment,
606 wall artifacts and slaking.

607 Simulated hydraulic conductivities could be very well predicted with the critical pore diameter for soil
608 samples from the no-till soil cores. However, the predictive power of the critical pore diameter even in
609 combination with other pore structure attributes was very low for cores from the conventionally tilled
610 soil and even lower for measured instead of simulated conductivities due to unavoidable inadequacies in
611 the measurements. Furthermore, the pore space attribute with highest predictive power on hydraulic
612 conductivity changes to macroporosity and pore connectivity in a narrow pressure range (from $h=0\text{cm}$ to
613 $h=-2\text{cm}$). This raises the question whether universal pedo-transfer functions for saturated and near-
614 saturated hydraulic conductivities based on X-ray CT derived macropore space properties are promising.
615 It needs to be tested on a larger dataset of structured soil that covers a larger variety of soil textures,
616 bulk densities and macroporosities, which of the investigated pore space attributes (or combinations
617 thereof) is the most robust in predicting (near-)saturated hydraulic conductivity.

618 Based on these findings we recommend that for constructing pedo-transfer functions for hydraulic
619 conductivity based on structural properties K_2 measurements are to be favored over K_s measurements
620 and the measurement technique should always be reported with the actual values when constructing
621 large databases.

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