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Effects of tillage intensity on pore system and physical quality of silt-textured soils detected by multiple methods

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Abstract. Understanding the effects of agricultural management practices on soil functionality is an ongoing challenge in environmental science and agricultural practice. In the present study we quantified the effects of changes in tillage intensity on soil physical quality and pore size distribution after 6, 10 and 23 years. At three long-term tillage experimental sites in central Europe we analysed soils under four different soil management systems: conventional mouldboard tillage; chiselling + rotary harrow; rotary harrow; and no till. These treatments differed in mechanical intensity and depth. Pore size distributions were calculated from soil water retention curves based on high-resolution measurements. Subsequently, fractions of functional pore size classes and indicators of soil physical quality were determined and compared between the treatments. In addition, we evaluated the performance of two calculation approaches for pore size distribution: (1) fitting of a smoothing cubic spline; and (2) a bimodal van Genuchten function. The parametric function yielded a higher proportion of storage pores by approximately 3–5%. The combination of multiple measurement and evaluation methods enabled detailed comparison of soil physical characteristics between different tillage treatments. No-till soils showed a distinct lack of transmissive pores and higher bulk density, but similar plant-available water capacity, compared with the other treatments. Under all soil management systems, aeration deficits were observed, emphasising the high vulnerability for compaction of silt-dominated arable soils with a low organic matter content. Hence, the design of agricultural soil management strategies on such soils needs to consider the risks of compaction as thoroughly as erosion or chemical degradation.

Additional keywords: high-resolution measurements, hydraulic soil properties, pore size distribution, soil degradation, soil management.

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Introduction

Pores, with their considerable different sizes and shapes, are the reaction zone of soil (Gupta *et al*. 2008). The soil pore size distribution (PSD), which is the fraction of distinct pore sizes in the whole pore system, determines the functionality of soil. This functionality is essential for civilisation and ensures the production of food, the cleaning of waste water or the storage of water and carbon. Especially valuable in times of changing climate and increasing demands on soil and water resources is the ability of soil to store water. Consequently, the loss of functional soil pore space, more generally physical soil degradation, is an actual global threat (Lal 2000; Eswaran *et al*. 2001; Commission of the European Communities 2006). Agriculturally used soils are most vulnerable and need to be protected and regenerated by adapted soil management strategies (FAO 2017).

The soil pore system is a combination of textural and structural pores (Lal and Shukla 2004). The former are generic voids between primary soil particles, whereas the latter originate from secondary soil formation processes, like aggregation, shrinking–swelling, freezing–thawing or biological activity. Of these two subsystems, only structure can be changed by soil management in order to improve the functionality of the soil, especially with a focus on water (Rabot *et al*. 2018). In arable land, optimisation of the tillage regime is thought of as means of improving soil structure. Hydrological and physical soil properties that are affected by tillage include water storage capacity, hydraulic conductivity or aggregate stability. However, for a meaningful evaluation of the advantages and restrictions of different tillage intensities, appropriate methods are needed that allow detailed analysis of the soil pore system and its functionality. Commonly used methods are either direct measurements from images, obtained from computed tomography (Grevers *et al*. 1989; Anderson and Hopmans 2013) or thin sections (Kubiena 1938; Elliot and Heck 2007), or indirect derivation from the soil water retention curve (SWRC; the relationship between soil water head h and volumetric water content θ) via the law of capillarity (e.g. Lal and Shukla 2004). The direct methods allow only analysis of the macropore system on reasonably sized samples due to limits in resolution (Schlüter *et al*. 2018). Nevertheless, a broad understanding of processes can be derived from such images, including the shapes of pores, organic particles and similar characteristics. The informative value of quantitative image analysis is highly dependent on methodological aspects such as resolution and image analysis algorithms (Anderson and Hopmans 2013). Conversely, indirect methods are based on model simplifications, which may imply uncertainty in the outcomes of soil physical studies (Kutilek 2004; Tuller and Or 2004). Indirect methods are commonly used at larger scales because they do not require expensive instruments and are less time consuming than direct methods. The results of such measurements provide valuable quantitative information about the effects of certain processes on linked soil functions and can be used directly for soil physical modelling.

The effects of different soil and land management strategies on soil pore characteristics and soil hydraulic properties have been the subject of extensive research (Horel *et al*. 2015; Schjønning *et al*. 2017; Blanco-Canqui and Ruis 2018). Different results have been reported as a consequence of tremendous variability in climate, soil texture and differences in soil management systems. Pires *et al*. (2017) characterised changes in the pore system of no-till (NT) and conventionally tilled (CT) soils using three-dimensional microscale computed tomography, micromorphological analyses of thin sections of impregnated blocks and indirect determination of PSD via the SWRC and fitting of a cubic spline. On clay soil in subtropical climate, Pires *et al*. (2017) found a larger, more complex pore system after 26 years of NT, supposedly caused by higher biological activity than under CT. In another study, only minor beneficial effects of NT were shown by Wairiu and Lal (2006), who used mercury porosimetry to detect PSD in two 38-year-old tillage experiments on silt loam. In contrast, Peña-Sancho *et al*. (2017) found lower porosity and a lack of macropores under NT as well as considerable seasonal variability in PSD under CT and reduced tillage (RT) on loam soil (23-year tillage experiment; SWRC derived from pressure plate apparatus). Kodesova *et al*. (2011) characterised macropore structure ($h > -70$ cm) under CT and 30 years grass coverage by inverse simulation of a multistep outflow experiment and micromorphological images of thin sections. Grassland soils, as an extreme case of NT, had more capillary pores and matrix pores than soils under CT. Similarly, Schwen *et al*. (2011) analysed the macroporosity of a silt loam in eastern Austria by inversely simulated tension infiltrometer experiments, finding found higher conductivity after 11 years of NT due to highly connective and less tortuous macropores compared with CT and RT, whereas CT and RT showed high seasonal variability in soil physical properties.

More generally, the review by Horel *et al*. (2015) summarised changes in soil hydraulic properties after a change in land use or soil management. As a main outcome, Horel *et al*. (2015) stated that negative effects, such as a decrease in plant-available water, increased bulk density and loss of soil organic matter, may be expected with intensifications in soil disturbance. The transformation of soil properties after a change in soil management strategies may last for several years or decades, especially on heavily textured soils. Nevertheless, Horel *et al*. (2015) also concluded that robust statements about the effects of distinct management strategies on the physical properties of soils are hampered by inconsistencies in scientific and agricultural methodology or the heterogeneity of soil.

Similarly, the analytical methodology used in the studies cited above is often not consistent. To achieve continuous results over the whole soil moisture range, a mathematical function needs to be approximated to measurements on the SWRC. To this end, two different approaches are primarily used: (1) a parametric function with the aim of condensing the information into a preferably small number of parameters; or (2) an interpolation via more complex functions, like a cubic spline defined by a vast number of parameters (Othmer *et al*. 1991). The latter method has the advantage of yielding approximations closer to measurements, and consequently allows a more precise interpretation of the resulting PSD. In contrast, parametric functions are the standard way to input soil physical properties into simulation models for soil water dynamics. Commonly, simple S- or C-shaped functions are fitted to the data. However, most soils show a more complex PSD, and the lack of flexibility in the function used may cause low goodness of fit and hamper the interpretation of differences between certain treatments (Durner 1994; Lozano *et al*. 2016). Hence, bi- or multimodal parametric functions are increasingly being used (Romano and Nasta 2016; Reynolds 2017). In this study we compared the two approaches using data measured by the evaporation method (Schindler *et al*. 2010) combined with dewpoint hygrometry (Campbell *et al.* 1973). We examined whether the choice of approximation scheme affects statements about soil physical quality (SPQ; Reynolds *et al*. 2009) and fractions of functional pore sizes (Lal and Shukla 2004), both of which were derived from the PSD.

The main objective of the present study was to quantify the changes in PSD in arable fields after a conversion from mouldboard ploughing to conservation tillage or NT. Consequently, the findings of the study would add information to the incomplete picture about the implications of different-intensity tillage strategies on the physical constitution of soil. The experimental locations were representative of silt-dominated arable soils under a temperate climate, which account for the biggest part of crop production in central Europe. To obtain highly informative and valuable results we applied a unique combination of different high-resolution measurement methods and evaluation approaches.

Materials and methods

Sampling sites and procedure

Soil sampling and experiments took place at three long-term tillage trials in north-eastern Austria and Saxony, Germany (Table 1). Four different tillage treatments had been established on the fields for 6, 10 and 23 years: (1) CT with a mouldboard plough and rotary harrow; (2) RT with a chisel plough and rotary harrow; (3) minimal tillage (MT) using only a rotary harrow; and (4) NT with a direct seeder. Intensive tillage operations (mouldboard and chisel plough) were conducted after harvest; before seeding of the subsequent cash crop, only the rotary harrow or direct seeder were used. Undisturbed soil samples were collected in steel cores (250 cm^3; inner diameter 8.4 cm, height 5 cm) at the soil surface, as were disturbed samples adjacent to the cores. Sampling was conducted between three and five times at the three sites throughout the vegetation period in 2016 (Table 2). Volumetric water content, θ, before sampling was between 0.20 and 0.35 $cm^3\ cm^{-3}$; hence, the soil was neither near saturation nor were drying cracks present on the soil surface, and the sampling points were placed in inter-row spaces to avoid machine tracks.

Measurement methods

The data for the retention curves (data pairs of θ and h) were obtained using the evaporation method and a HYPROP device (METER Group, Munich, Germany; Schindler *et al*. 2010) and a dew point hygrometer (WP4C PotentiaMeter; METER Group). In addition, hood infiltrometer (Schwärzel and Punzel 2007) experiments were conducted to measure hydraulic conductivity in the near-saturated range, bulk density was measured by oven drying (105°C, 24 h) of 250-cm^3 core samples and saturated hydraulic conductivity was measured in the laboratory using the falling head method (Reynolds and Elrick 2002). The sampling and measurement procedures have been described in detail elsewhere (Weninger *et al*. 2018). Failure in one of the methods used was inevitable in single cases, and in such cases data from the whole respective dataset (i.e. sampling point) had to be excluded from further analyses. This explains the discrepancy between maximum possible data extent calculated from Table 2 and actual data extent in Table 3.

Data processing and statistics

Retention curves for each experimental plot were approximated to measured data using two different approaches: a cubic spline and a bimodal van Genuchten (bVG) function (Othmer *et al*. 1991). First, values for soil water head h were transformed to pF values (pF = $\log_{10}(h)$). The density of data points over the pF range was very heterogeneous, hence data were classified with a class width of 0.2 pF to balance weights of measurements. The means of all data inside the respective classes were used as nodes for the fitting. The high flexibility of the cubic spline led to implausible oscillations in the resulting curve in the transition zone between the measurement ranges of the two combined methods. Consequently, we used a smoothing cubic spline (sCUB) to balance these irregularities (R Core Team 2016; smoothing parameter = 0.5). The fitting yielded two continuous functions (sCUB and bVG) for each sampled point, which were used to predict θ for the centres of pF classes (width 0.2, as above). Subsequently, the predicted class centre

Table 1. Descriptions of study sites

Texture classification was as follows: 2 mm > sand $\geq$ 0.063 mm > silt $\geq$ 0.002 mm > clay (British Standards Institution 2018). WRB, World Reference Base

	Site A	Site B	Site C
Location name	Lüttewitz (Germany)	Hollabrunn (Austria)	Obersiebenbrunn (Austria)
Crop	Winter wheat	Winter wheat	Sunflower
Soil texture (sand/silt/clay; g g^{-1})	0.03/0.78/0.19	0.24/0.55/0.21	0.34/0.50/0.16
Soil type (WRB)	Luvisol	Chernozem	Chernozem
Mean annual precipitation (mm)	650	520	520
Mean annual temperature (°C)	8.5	9.0	9.4
Altitude (m above sea level)	270	235	150
Soil organic carbon[A] (g kg^{-1})	10–20	10–20	10–20
Year tillage experiment established	1993	2006	2010

[A]Values for soil organic carbon were derived in several campaigns over recent years (Bodner G, Weninger T, unpubl. data); thus, the values are not results of the present study and a range is given.

Table 2. Data composition

Treatments, in order of decreasing tillage intensity, are conventional tillage (CT), reduced tillage (RT), minimal tillage (MT) and no tillage with direct seeding (NT). Site A is in Lüttewitz (Germany), Site B is in Hollabrunn (Austria) and Site C is in Obersiebenbrunn (Austria)

	Site A	Site B	Site C
Treatments	CT, RT, MT, NT	CT, RT, MT, NT	CT, RT, MT, NT
No. measurement campaigns	5	3	4
No. treatment replicates per campaign	5 for all	3, 11, 3	11, 3, 3, 3

Table 3. Selected soil physical properties measured at three long-term tillage trials in Lüttewitz, Germany (Site A), Hollabrunn, Austria (Site B) and Obersiebenbrunn, Austria (Site C)

Within each site, different letters in the 'Group' column indicate significant differences among treatments (Tukey's HSD test, $P = 0.05$). For a detailed description of each of the sites, see Table 1. n, number of observations; $K_{s(FH)}$, saturated hydraulic conductivity (cm day^{-1}) measured by the falling head laboratory method; $K_{s(HI)}$, is saturated conductivity (cm day^{-1}) measured by a hood infiltrometer; CT, conventional tillage; RT, reduced tillage; MT, minimal tillage; NT, no tillage and direct seeding

Site	Treatment	n	$\log_{10}(K_{s(FH)})$			$\log_{10}(K_{s(HI)})$			Bulk density (g cm^{-3})			Porosity (cm^3 cm^{-3})		
			Mean	CV	Group	Mean	CV	Group	Mean	CV	Group	Mean	CV	Group
A	CT	25	2.55	0.30	a	2.81	0.15	a	1.30	0.06	a	0.509	0.06	a
	RT	16	3.45	0.04	b	3.03	0.11	b	1.14	0.08	b	0.570	0.06	b
	MT	19	2.61	0.25	a	3.02	0.15	ab	1.29	0.06	a	0.514	0.06	a
	NT	19	2.63	0.26	a	2.64	0.11	a	1.34	0.05	a	0.494	0.05	a
B	CT	17	3.11	0.27	a	2.78	0.18	a	1.27	0.07	a	0.520	0.07	a
	RT	14	3.39	0.24	a	2.73	0.13	a	1.27	0.08	a	0.520	0.07	a
	MT	18	2.52	0.41	a	2.61	0.13	a	1.34	0.06	a	0.494	0.06	a
	NT	16	2.58	0.45	a	2.49	0.18	a	1.51	0.04	b	0.429	0.05	b
C	CT	20	2.85	0.26	ab	2.27	0.18	ab	1.30	0.07	a	0.510	0.06	a
	RT	11	3.18	0.20	a	2.42	0.11	a	1.26	0.05	a	0.526	0.05	a
	MT	20	2.90	0.24	ab	2.52	0.10	a	1.25	0.06	a	0.529	0.05	a
	NT	20	2.37	0.36	b	2.05	0.16	b	1.40	0.04	b	0.471	0.04	b

Table 4. Soil physical parameters and indicators for soil physical quality evaluated

Abbreviation	Description
$K_{s(FH)}$	Saturated hydraulic conductivity, measured by the falling head laboratory method (units used herein: cm day^{-1})
$K_{s(HI)}$	Field-saturated hydraulic conductivity measured by a hood infiltrometer (cm day^{-1})
ρ_d	Bulk density from oven drying of soil core samples of a defined volume (g cm^{-3})
P	Porosity; volume of pores divided by the total, undisturbed volume (cm^3 cm^{-3}), calculated as follows: $1 - \rho_d/2.65$
PAWC	Plant-available water capacity (cm^3 cm^{-3}); water volume stored between h = 100 cm and h = 15 000 cm
AC	Air capacity (cm^3 cm^{-3}); air-filled pore volume at h = –100 cm
RFC	Relative field capacity (cm^3 cm^{-3}), calculated as 1 – (AC/P)

values of all corresponding replicates (same site and treatment) were pooled (the sample size at this point is given in Table 3, column n) and the mean, s.d. and CV were calculated and analysed.

Three different outcomes were used to evaluate the results: (1) graphical interpretation of curves; (2) classification into functional pore size classes after Greenland (1981); and (3) capacity-based indicators for soil physical quality (Reynolds *et al*. 2009). For the graphical interpretation of curves, water content data (predicted as described above) was normalised by the maximum observed water content, θ_{max} (approximation for saturated water content, θ_s), yielding effective saturation, $S_e(h)$. Results for the same site and treatment were averaged and plotted together with the first derivative of $S_e(h)$, which corresponds to the PSD.

For the second and third outcomes, absolute values for θ were used and the conversion between soil water head h on the retention curve and the corresponding pore diameter was made using the simplified capillary equation $h = 1490r^{-1}$ (where h is soil water head (cm) and r is the equivalent pore radius (μm)). Following Greenland (1981), pores with a calculated diameter >500 μm were classified as fissures, those with diameters between 50 and 500 μm were classified as transmissive pores, those with diameters between 0.5 and 50 μm were classified as storage pores, those with diameters between 0.005 and 0.5 μm were classified as residual pore, and those with a diameter <0.005 μm were classified as bonding pores. The predicted values for the borders of classes were interpolated, the fractions of pore volume in the different pore classes were calculated and the results for the same site and treatment were averaged and analysed statistically for differences between treatments. For the third evaluation approach, soil physical parameters and capacity-based indicators for SPQ (Reynolds *et al*. 2009) were calculated according to Table 4. The selected indicators are widely used for interpretation of SPQ and ensure comparability to similar studies.

All data was processed using R version 3.3.1 (R Core Team 2016). Normality or log-normality of selected results for comparison of treatment effects was tested by visual interpretation of Q–Q plots. Saturated hydraulic conductivity values derived by falling head laboratory method ($K_{s(FH)}$) and in the field by hood infiltrometer experiments ($K_{s(HI)}$) were represented best by a log-normal distribution; other metrics followed a normal distribution. The significance of differences between treatments was analysed by analysis of variance (ANOVA), with Tukey's honestly significant difference (HSD) test used as post hoc test to define coherent groups (de Mendiburu 2016). A paired t-test was used to detect significant differences between results derived by the two approximation approaches.

Results and Discussion

Effects of tillage intensity on physical soil conditions

Results of measured soil physical properties are given in Table 3, and SPQ indicators calculated from the retention curve are given in Table 5. $K_{s(FH)}$ and $K_{s(HI)}$ enable inference of the presence of connective macropores (fissures and transmission pores according to the classification used) because the water flow measured predominantly occurs through these pores. No consistent differences between treatments were found, but most of the lowest conductivities were found under NT systems and highest conductivities under the RT and MT systems (Table 3). These findings are in agreement with the review of Blanco-Canqui and Ruis (2018), who did not find systematic effects of tillage on saturated hydraulic conductivity. Nevertheless, Blanco-Canqui and Ruis (2018) identified more distinct differences for infiltration capacity, which was highest under NT. Furthermore, NT soils showed higher values of bulk density, ρ_d, than other treatments at two of the three sites (Table 3), which is in accordance with 24 of 62 available studies reviewed by Blanco-Canqui and Ruis (2018). However, in medium-textured soils (the term used in comparison with sandy and clayey or fine-textured soil by Blanco-Canqui and Ruis 2018, hence comparable to the soils sampled herein), 18 of 24 studies reviewed by Blanco-Canqui and Ruis (2018) found significantly higher ρ_d under NT. This agreed with the fact that medium-textured or silt-dominated soils are especially vulnerable to compaction by clogging of pores (Horn *et al*. 1995). In the present study results, air capacity (AC) was also distinctly lower under NT, whereas plant-available water capacity (PAWC) was in the same range as for all other treatments. In contrast, no systematic limitations in AC under NT were found by Reynolds *et al*. (2009), who analysed 13 soils containing less silt, and Lozano *et al*. (2016) on an Argentinian loam with soil organic carbon (SOC) content of 40–56 g kg^{-1}. Consequently, higher SOC content could decrease the vulnerability of the sampled soils to compaction, and an improvement may be expected after a longer period of NT management (Murphy 2015; Blanco-Canqui and Ruis 2018).

Classifying SPQ indicators in terms of their agricultural usability (Reynolds *et al*. 2009) showed that, regardless of treatment, all soils sampled except one (ρ_d = 1.14 g cm^{-3}) had too-high ρ_d, with values ranging from 1.25 to 1.51 g cm^{-3} (Table 3; the optimal ρ_d range for loamy soils is between 0.9 and 1.2 g cm^{-3}; Reynolds *et al*. 2009). Similarly, results for relative field capacity (RFC) were between 0.724 and 0.900 cm^3 cm^{-3} (except for one soil, in which RFC was 0.673 cm^3 cm^{-3}), indicating potential yield losses due to a lack of aeration (Table 5; the optimal RFC range is between 0.6 and 0.7 cm^3 cm^{-3}). Results for AC followed the same trend even though the variability between treatments and sites was higher, and certain soils could be denoted as optimal (>0.14 m^3 m^{-3}), whereas in others aeration was poor (<0.10 m^3 m^{-3}). The PAWC was at least 0.203 m^3 m^{-3}, hence ideal in all soils (optimal range >0.20 m^3 m^{-3}). This may also be explained by the high fraction of silt together with low organic matter content (e.g. Horn *et al*. 1995).

Pore size distribution

All SWRCs and their derived PSDs are compared in Figs 1 and 2. Interpretations were based on sCUB (Fig. 1) because it represented measured data better than bVG. The most intensive treatment CT showed a distinct bimodal character for PSD at all sites. In all three tillage experiments there was an obvious difference between NT and all other treatments, which showed a mode (peak) in the range of transmissive or course

Table 5. Soil physical quality indicators calculated from retention curves for the three sites in Lüttewitz, Germany (Site A), Hollabrunn, Austria (Site B) and Obersiebenbrunn, Austria (Site C)

Within each site, different letters in the 'Group' column indicate significant differences among treatments (Tukey's HSD test, P = 0.05). For a detailed description of each of the sites, see Table 1. AC, air capacity; PAWC, plant-available water capacity; RFC, relative field capacity; VG, bimodal van Genuchten model; CT, conventional tillage, RT, reduced tillage; MT, minimal tillage; NT, no tillage and direct seeding

	PAWC (cm^3 cm^{-3})						AC (cm^3 cm^{-3})						RFC (cm^3 cm^{-3})						Relative difference of means (VG – spline)		
	Cubic spline			VG			Cubic spline			VG			Cubic spline			VG					
	Mean	CV	Group	Mean	CV	Group	Mean	CV	Group	Mean	CV	Group	Mean	CV	Group	Mean	CV	Group	PAWC	AC	RFC
Site A																					
CT	0.286	0.09	a	0.299	0.12	ab	0.089	0.43	a	0.079	0.59	a	0.827	0.08	a	0.847	0.10	a	0.013	–0.010	0.020
RT	0.320	0.12	b	0.339	0.16	c	0.126	0.41	b	0.114	0.58	a	0.780	0.11	a	0.802	0.13	a	0.019	–0.012	0.022
MT	0.259	0.16	c	0.276	0.18	a	0.104	0.43	ab	0.095	0.62	a	0.801	0.10	a	0.820	0.13	a	0.017	–0.009	0.019
NT	0.298	0.08	ab	0.325	0.07	bc	0.052	0.43	c	0.031	0.62	b	0.897	0.05	b	0.938	0.04	b	0.027	–0.020	0.041
Site B																					
CT	0.223	0.15	ab	0.238	0.17	ab	0.174	0.38	a	0.162	0.43	a	0.673	0.16	a	0.695	0.17	a	0.015	–0.011	0.022
RT	0.243	0.14	a	0.259	0.18	a	0.132	0.35	ab	0.121	0.43	ab	0.750	0.10	b	0.770	0.12	ab	0.016	–0.011	0.020
MT	0.244	0.06	a	0.254	0.07	a	0.103	0.32	b	0.099	0.34	b	0.793	0.07	b	0.803	0.07	b	0.009	–0.005	0.009
NT	0.203	0.13	b	0.219	0.17	b	0.054	0.46	c	0.046	0.66	c	0.876	0.07	c	0.893	0.08	c	0.015	–0.008	0.018
Site C																					
CT	0.246	0.09	a	0.270	0.13	ab	0.143	0.33	a	0.118	0.49	a	0.724	0.11	a	0.773	0.13	a	0.023	–0.024	0.049
RT	0.263	0.06	ab	0.298	0.10	a	0.134	0.25	a	0.099	0.44	a	0.748	0.08	a	0.814	0.09	a	0.035	–0.035	0.066
MT	0.271	0.06	b	0.263	0.15	b	0.134	0.35	a	0.115	0.52	a	0.750	0.11	a	0.786	0.13	a	–0.008	–0.019	0.036
NT	0.255	0.08	ab	0.287	0.10	ab	0.074	0.32	b	0.044	0.63	b	0.843	0.06	b	0.908	0.06	b	0.032	–0.031	0.065
																		Mean	0.017	–0.016	0.032

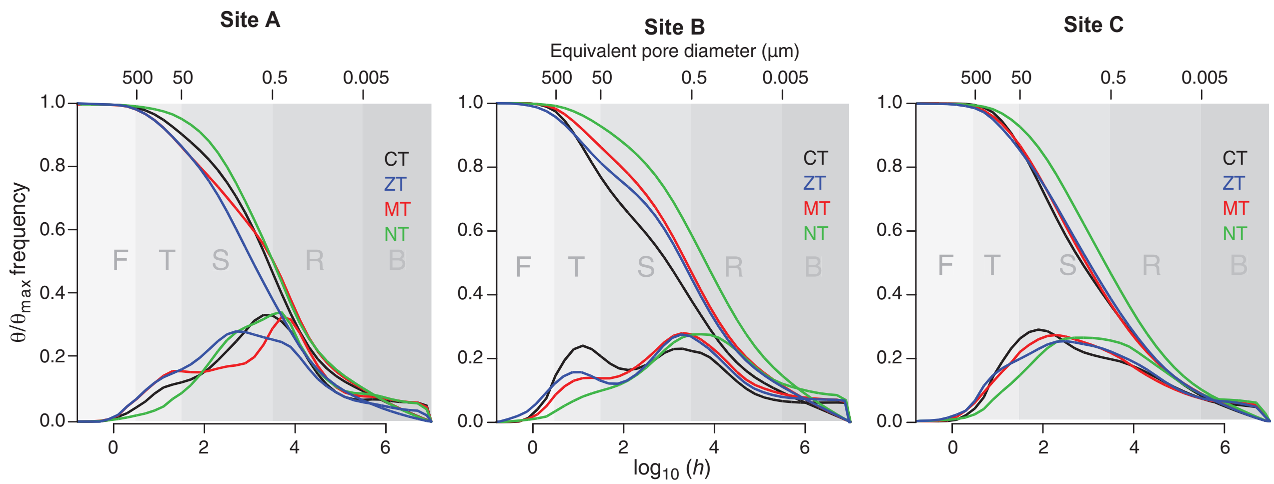

Fig. 1. Relative soil water retention curves (lines starting from 1.0) and deviated pore size distributions (lines starting at 0.0) derived by fitting a smoothing cubic spline for different treatments (CT, conventional tillage; RT, reduced tillage; MT, minimal tillage; NT, no tillage and direct seeding) at Site A (Lüttewitz, Germany), Site B (Hollabrunn, Austria) and Site C (Obersiebenbrunn, Austria). Different shades of grey indicate functional pore size classes (Greenland 1981), as follows: F, >500 µm (fissures); T, 50–500 µm (transmission pores; important for water movement and gas exchange); S, 0.5–50 µm (storage pores; retention against percolation); R, 0.005–0.5 µm (residual pores; retention and diffusion of ions in solution); B, <0.005 µm (bonding pores). Soil water head, *h*, was measured in centimetres. θ, volumetric water content; θ_{max}, maximum observed water content.

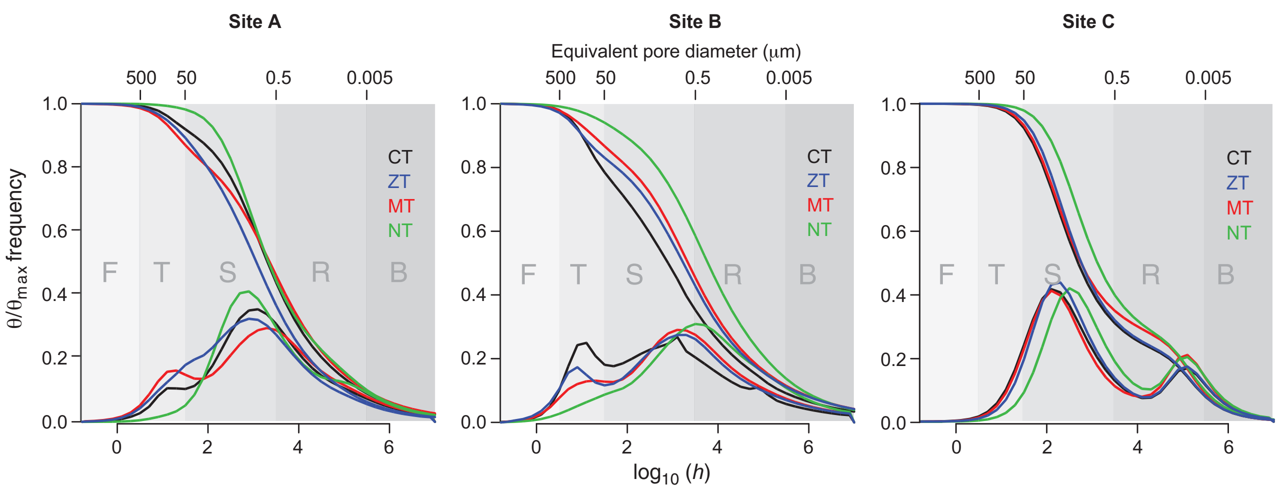

Fig. 2. Relative soil water retention curves (lines starting from 1.0) and deviated pore size distributions (lines starting at 0.0) derived by fitting of a bimodal van Genuchten function for different treatments (CT, conventional tillage; RT, reduced tillage; MT, minimal tillage; NT, no tillage and direct seeding) at Site A (Lüttewitz, Germany), Site B (Hollabrunn, Austria) and Site C (Obersiebenbrunn, Austria). Different shades of grey indicate functional pore size classes (Greenland 1981), as follows: F, >500 µm (fissures); T, 50–500 µm (transmission pores; important for water movement and gas exchange); S, 0.5–50 µm (storage pores; retention against percolation); R, 0.005–0.5 µm (residual pores; retention and diffusion of ions in solution); B, <0.005 µm (bonding pores). Soil water head, *h*, was measured in centimetres. θ, volumetric water content; θ_{max}, maximum observed water content.

storage pores. This mode was not present in the NT treatment, which was surprising because NT was expected to have more biologically built macropore, such as earthworm burrows or decayed roots (e.g. Wairiu and Lal 2006; Schwen *et al*. 2011; Alvarez *et al*. 2014). Fig. 3 shows quantitative comparison of pore volume belonging to functional pore size categories. On average, NT soils had 0.082 m^3 m^{-3} less transmission pores than the other treatments (referring to total pore volume; s.d. = 0.095). In contrast, the NT treatment was richer in residual pores. Results from comparable studies using a coarser, size-based classification were variable without a uniform trend (Blanco-Canqui and Ruis 2018). In contrast with the present study, significantly lower fractions of storage and transmission pores were found in CT than in several types of conservation tillage by Pagliai *et al*. (2004) and Abdollahi and Munkholm (2017).

The variability between PSD curves of the same treatment was exceptionally low, as evidenced by the resulting indicators for SPQ (Table 5) and functional pore size classification (Fig. 3). Especially for CT, we expected comparably higher temporal variability due to seasonal changes (e.g. Tebrügge and Düring 1999; Kargas *et al*. 2016; Soracco *et al*. 2018). Most

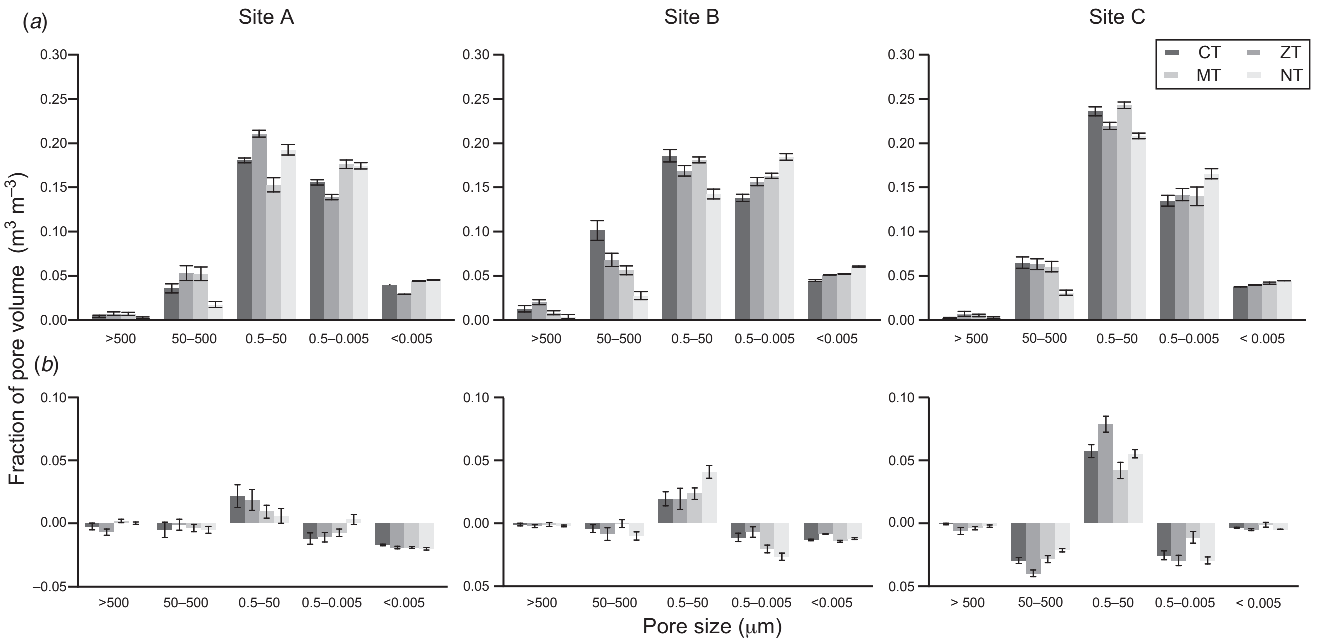

Fig. 3. (*a*) Pore size volume fractions in functional pore size classes relative to total bulk volume for different treatments (CT, conventional tillage; RT, reduced tillage; MT, minimal tillage; NT, no tillage and direct seeding) at Site A (Lüttewitz, Germany), Site B (Hollabrunn, Austria) and Site C (Obersiebenbrunn, Austria). Class boundaries were detected by interpolation using smoothing cubic splines. (*b*) Corresponding differences between pore size volume fractions obtained using cubic spline fitting and the bimodal van Genuchten model for soil water retention curves (positive results indicate a higher value obtained using cubic spline fitting). Functional pore sizes were classified as follows: >500 μm, fissures; 50–500 μm, transmission pores (important for water movement and gas exchange); 0.5–50 μm, storage pores (retention against percolation); 0.005–0.5 μm, residual pores (retention and diffusion of ions in solution); <0.005 μm, bonding pores. Data show the mean ± s.d.

likely the low variability between single samples within the same treatment resulted from the normalisation with θ_{max}. Consequently, in future studies measurements will be adapted and extended to analyse the seasonal variability of the characteristics examined for multiple vegetation periods. The focus of the present study was on long- and mid-term changes (6, 10, 23 years) of soil physical conditions due to different tillage intensity, and the low variability during the sampled period strengthens the results and interpretations.

Effects of fitting procedure

Soil physical parameters derived from retention curves can be affected by the type of fitting procedure applied to the measured $\theta(h)$ data points. We tested two different approaches to derive continuous retention curves and quantified the differences in the evaluation metrics (Table 5). The differences were significant for all indicators, as analysed by paired *t*-tests ($\alpha = 0.05$). Using bVG rather than sCUB resulted in an overestimation of PAWC and an underestimation of AC of <2%, whereas RFC was overestimated by approximately 3%. This resulted in a higher proportion of samples where AC was classified as poor. In contrast, the resulting classification of PAWC (ideal) and RFC (potentially lacking aeration) did not differ between the two approaches. The fitting of the bVG function yielded a higher variability in SPQ metrics that was the result of lower goodness of fits compared with the more flexible and data-driven sCUB (Othmer *et al*. 1991; Kastanek and Nielsen 2001). Nevertheless, the effective differences between the two approaches after pooling replicate data were distinctively smaller than on single measurements as reported by Othmer *et al*. (1991). Hence, appropriate replication increases the possibility of detecting differences in PSD or SPQ between certain soil management regimes also using the less flexible parametric function (bVG). Bimodal functions should be used, because the lack of flexibility in unimodal functions may hamper the detection of such differences in certain soils (Lozano *et al*. 2016).

The most distinct differences between retention curves derived by the two different functions were visible at Site C (Obersiebenbrunn, Austria). There, bVG exhibited clear bimodality with a second mode in the range of residual pores (Fig. 2). The sCUB at Site C followed an irregular unimodal shape, whereas other sites were more similar to bimodality (Fig. 1). This may be interpreted as tendency of bVG to yield poor fits to irregularly shaped retention data because there is a certain probability that a second mode is detected even if it is not fully supported by measurements. This is in contrast with the results of Romano and Nasta (2016), who found benefits in using bimodal functions even for weakly bimodal PSD. Fig. 3*b* again shows that using the parametric bVG function overestimated storage pores, which determine PAWC, compared with sCUB. However, considerable differences regarding larger pores responsible for aeration were only found at Site C, where the overall pattern showed least bimodality in pore size distribution.

Conclusions and relevance

The use of a cubic spline function was found to be preferable to the parametric bVG model due to higher flexibility, especially for irregularly shaped data. We also found significant differences between the two approaches when used as a basis for a functional classification of the soil pore system.

The soils analysed were silt dominated and showed a lack of aeration, whereas water capacity was optimal. The higher bulk density of the NT system compared with the other tillage treatments was primarily related to a lower fraction of large, aerated pores. Graphical representation of PSD revealed this lack of transmissive pores in NT soils, whereas NT soils had higher PAWC. Additional analysis of indicators for SPQ confirmed these interpretations, and low organic matter content increased the vulnerability of the soil to compaction. Although silt-dominated soils are most endangered by erosion and thus target sites for RT systems, a loss of aeration has to be controlled to avoid adverse conditions for root aeration, plant growth and consequently yield. The results presented herein are representative of a significant portion of the agricultural soils in central Europe, and the methodology allows sound and detailed interpretations. Future advances in modelling of changes in soil pore systems based on such results will improve the opportunities for the development of sophisticated agricultural management strategies.

Conflicts of interests

The authors declare no conflicts of interest.

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