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Improvements in soil physical properties after long-term manure addition depend on soil and crop type

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ABSTRACT

Manure application and crop rotation are common agricultural practices that can alter soil physical properties and affect soil functions. In this study, we assessed the effect of long-term manure fertilization (24 to 126 years) and crop type on soil hydraulic, aggregate and pore structural properties. Samples were collected from three long-term experiments (LTEs) in Sweden (silty clay, SiC), Germany (silt loam, SiL) and Denmark (sandy loam, SL). Measurements included water retention, air permeability and gas diffusivity measured at five matric potentials −3, −5, −10, −30 and −50 kPa, saturated hydraulic conductivity (K_{sat}), bulk density (ρ_b), and water-stable aggregates (WSA). The treatments at the three LTEs included various manure rates and crop sequences (winter wheat, maize, spring barley, and grass/clover). Results showed that long-term manure addition reduced ρ_b by an average of 3–6% for all three sites, and improved soil water retention, plant available water and WSA for most investigated plots. However, increasing manure rates for the SiL and SL sites did not result in further improvements in soil water retention, ρ_b and water-stable aggregates. The effect of manure on soil pore size distribution, gas transport, and K_{sat} varied with soil and crop type. Manure increased the porosity of pores < 30 μm in the two fine-textured sites and increased the porosity of pores > 30 μm for wheat and maize plots in the SL site. Manure improved gas transport and K_{sat} in the wheat plots and decreased these properties in the barley plots regardless of soil texture. The maize plots in the SL site had well developed pore structure, while the pore structure in the SiL site was relatively poor. Grass plots had poorer gas transport than maize plots in the SL site despite the manure addition. The study shows that improvements in soil physical and chemical properties arising from manure application largely depend on the crops grown and the soil texture.

1. Introduction

Manure application and crop rotation are two common agricultural practices that usually increase soil organic carbon (SOC) content and crop yield, and enhance soil quality (Bai et al., 2018). The best outcome of these practices requires long-term strategic planning because it takes at least 20 years to detect the change in SOC and several years to correct the problem that stemmed from a bad rotation plan (Bolluyt et al., 2009; Rasmussen et al., 1998). Therefore, long-term experiments (LTEs) are highly valuable in agricultural studies to identify the effect of a certain practice on soil quality and crop yield (Rasmussen et al., 1998).

Long-term manure application has proven to improve soil physico-chemical, hydraulic and structural properties (Haynes and Naidu, 1998). The most noticeable change from long-term manure application is the increase of SOC which in turn influences other soil properties, e.g. by decreasing bulk density (ρ_b) and increasing water retention (Blanco-Canqui et al., 2015). As a binding agent, SOC also increases water-stable aggregates (WSA) which also affects the soil pore size distribution (Jensen et al., 2017). Additionally, manure could alter soil pH and electrical conductivity (EC), which could further influence microbial activity and soil aggregation (Lin et al., 2019). Manure application can enhance earthworm activities, which can lead to an increase in macroporosity (Naveed et al., 2014). The magnitude of the above-mentioned impacts of manure on soil properties also depends on the soil particle size distribution (soil texture). Because of the change in pore structure caused by manure, soil gas transport including gas diffusion and air permeability, and saturated hydraulic conductivity (K_{sat}) are expected to change with the manure rate. However, there seems no conclusive

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general patterns of gas transport and K_{sat} associated with manure addition (Eden et al., 2012; Schjønning et al., 2005, 2002). The comparison of physical properties, especially gas transport and K_{sat}, between different textured soils under long-term manure application still needs further investigation.

The change in the physicochemical, hydraulic and structural properties under different crop rotations varies with the combination of rotation elements (Bullock, 1992). In a good crop rotation cash crops are followed by ley pastures or green manure cover crops (Bolluyt et al., 2009). The inclusion of a long period of perennial pasture could increase SOC, while the arable rotation without cover crops often causes a loss of SOC (Hu and Chabbi, 2022). Jensen et al. (2019) reported that soil structural stability increased with an increase in SOC, and the arable-ley rotation had higher SOC than the arable rotation in Highfield LTE in Rothamsted. Different crops have different root systems and the distinct difference between grassroots and cereal roots could result in a difference in soil pore structure, with consequences on gas transport and K_{sat}. Schjønning et al. (2002) found higher K_{sat} in crop rotation with 2 yrs ley than the rotation of annual crops, nevertheless, slight or insignificant differences were found in pore size distribution and gas transport.

Crop sequence is important in crop rotation as one crop can affect the following crop by nutrient removal, development of biopores and other changes related to root growth (Ball et al., 2005). Thus, it is important to evaluate the impact of each rotation element on soil properties. Garcia et al. (2013) reported the ρ_b, total porosity and aggregate size distribution at the end of each rotating crop growing period under no-till, and there were significant differences between each rotation element, attributed to differences in root systems. By mixing deep root and shallow root crops, the authors concluded that the tillage was no longer needed. Despite the importance of individual crops, many studies focus on the accumulative effect of crop rotation on soil properties between different crop sequences. There is a paucity of information on the effect of each rotation element on soil properties, particularly physical properties, during the crop growing period. Furthermore, as a source of nutrients, manure application is often combined with crop rotation. Thus, it is important to investigate further how manure interacts with the crop rotation elements and how this interaction is reflected in physical properties and functions of soils.

Based on the gaps in the current knowledge, we hypothesized that 1) long-term manure application will improve soil hydraulic and structural properties regardless of soil type; 2) the improvement of soil properties after manure application will be greater in coarse-textured soils than in fine-textured soils; 3) crop type will interact strongly with manure to modify soil properties. To test the hypotheses, the objectives were to 1) examine the effect of long-term manure addition on soil hydraulic and structural properties for three soil types; 2) assess the interaction of crop types with manure amendment and its influence on soil physicochemical properties. Soil structural properties in this study include ρ_b, WSA and soil pore structure which is characterised by pore size distribution derived from soil water retention and pore morphology measured by gas transport.

2. Materials and methods

2.1. Description of sites and sampling

The study involved three LTEs that had contrasting soil textures (silty clay, silt loam and sandy loam) and different levels of manure treatment. The silty clay-textured LTE is located at the Lanna agricultural research station (58°21′N, 13°08′E) in Sweden and the experiments were started in 1996. The soil is an Aquic Haplocryept (Kätterer et al., 2014; Soil Survey Staff - NRCS/USDA, 2014). Mean annual temperature and precipitation are 636 mm and 7.3 °C (1997–2009), respectively (Kätterer et al., 2014). To study the effects of manure on soil, three treatments from this experiment were selected: bare fallow (BF), 38 t ha^{-1} 2 yrs^{-1} (38 t) farmyard manure (fresh cattle manure with straw bedding) and unfertilized arable field (UNF). The treatments were randomized in four blocks and the plot size is 8 × 14 m. Oat (10 years), spring barley (4 years), spring wheat (1 year) and winter wheat (w.wheat, 3 years) were grown during the period 2002–2019. Once every two years in autumn, 38 t ha^{-1} manure containing 10 t ha^{-1} dry matter (approx. 4 t ha^{-1} C) is added to the field before ploughing (Kätterer et al., 2014). The last manure addition before sampling for this study was in autumn 2018. All the plots were mouldboard-ploughed to a depth of 15 cm, followed by shallow cultivation by a tandem disk to a depth of 10 cm in September 2019 before sowing the winter wheat for the cropped fields. The BF plots were normally harrowed 4–5 times by coil tine harrow to a depth of 5 – 8 cm during the growing season. It should be noted that the BF plots were not harrowed during the season when the sampling for this study was done. That year, weeds were controlled manually.

The silt loam-textured LTE is the static fertilization experiment in Bad Lauchstädt, Germany (51°24′N, 11°53′E) and was established in 1902. The soil at the experimental site is classified as a Typic Mollisol (Soil Survey Staff - NRCS/USDA, 2014). Mean annual temperature and precipitation are 484 mm and 8.7 °C, respectively (means from 1896 to 2004) (Eden et al., 2012). The 4-ha field is divided into eight strips and the size of each plot is 10 × 26.5 m. Due to the large size of each plot, treatments are laid out in the field without replicates. The treatments considered for this work were UNF, 20 t ha^{-1} 2 yrs^{-1} (20 t) and 30 t ha^{-1} 2 yrs^{-1} (30 t) farmyard manure (from cattle barn) in the spring barley (strip 2) and maize plots (strip 6). Both plots were rotated with the same crop sequence, i.e. spring barley, maize and winter wheat. The amount of manure is given in fresh weight and the dry matter varied from 15% to 46% and the carbon content of the dry matter was around 40%. The manure in strip 2 was added in autumn 2018 and the manure in strip 6 was added in autumn 2019 before ploughing. The barley plots were first harrowed by a layered cultivator to a depth of 15 cm and a roundabout cultivator to a depth of 8 cm in September. The maize plots were harrowed two times to a depth of 8 cm by using a disk tandem harrow. After one month, all the plots were ploughed using a 3 mouldboard two-way turnover plough to a depth of 28 cm. The top 5 cm was tilled by a short combination fine cultivator in March the following year before sowing for all treatments. More information is given by Merbach and Schulz (2013).

The sandy loam-textured LTE is at the Askov research station in Denmark (55°28′N, 09°07′E) and was initiated in 1894. The mean annual temperature and precipitation are 869 mm and 7.7 °C, respectively (means of 1961–1990) (Jensen et al., 2017). The soil is classified as a Typic Hapludalf (Soil Survey Staff - NRCS/USDA, 2014). The experiments were conducted in four field blocks denoted B2 – B5. The size of each plot in blocks B3 to B5 was 11.68 × 9.40 m while the plots in the B2 block were 7.33 × 9.40 m each. For this study, three levels of manure application with three replicates from each field block were selected: UNF, 25 t ha^{-1} yr^{-1} (25 t) and 37.5 t ha^{-1} yr^{-1} (37.5 t) cattle slurry in fresh weight. The dry matter of the slurry was in average 5% and the total C in the slurry was approximately 44% (Jensen et al., 2022). The crops growing in the four blocks at the time of soil sampling were, per the rotation sequence, w. wheat, silage maize, spring barley and grass/clover mixture (including *Medicago sativa* L., *Trifolium hybridum* L., *Lotus corniculatus* L., *Lolium perenne* L., *Festuca pratensis* Huds. and *Phleum pratense* L.). The grass/clover mixture was under-sown with spring barley and when the barley was harvested, the grass/clover mixture (referred to as grass plots hereafter) was left in the field as a rotation element until August of the following year. The cattle slurry was added in March/April to the surface of w. wheat plots and before ploughing for barley and maize plots. The fields were mouldboard-ploughed to a depth of 18 – 20 cm in March/April for spring-sown crops and in September for the autumn-sown crop. After ploughing, the soil was harrowed and seeds were sown using a rototiller combined with a drill. Tillage was the same for all treatments for each crop type. More information is given by Christensen et al. (2019).

Soil sampling took place from July through August 2020. The duration between the last ploughing and sampling is as follows. In Lanna, the duration was 322 days. In Bad Lauchstädt, the duration for barley plots was 281 days and for maize was 302 days. In Askov, the duration for wheat plots was 328 days, for maize plots 153 days, for barley plots 139 days and for grass plots 541 days. In each plot, three undisturbed steel soil cores (100 cm^3, 6.1 cm in diameter, 3.5 cm in height) and bulk soil were collected from the 5 – 15 cm soil layer at three different spots in the plot. The extracted soil cores and bulk soil samples were sealed and stored at 2 °C before laboratory measurements.

2.2. Soil texture and chemical properties

The bulk soil was air-dried, ground, and sieved through a 2 mm mesh for the measurements of basic soil characteristics. Soil texture was determined by a combined hydrometer and wet sieving method after the removal of soil organic matter with hydrogen peroxide (Gee and Or, 2002). Soil organic carbon was determined on ball-milled aliquots by oxidizing C at 950 °C with a Thermo Flash 2000 NC Soil Analyzer (Thermo Fisher Scientific, USA). Plant available potassium and magnesium were extracted by ammonium acetate and measured with an atomic absorption spectrophotometer (Perkin-Elmer Analyst 300, US). A modified protocol from Sissingh (1971) was adapted for the measurement of water-extractable phosphorus (P_w). Briefly, 1 g of soil was pre-wetted with 1 mL demineralized water for 17 h followed by adding 49 mL demineralized water and shaking for 1 h at 20 °C. The suspension was then centrifuged at 5000 rpm for 10 min and the supernatant was analysed for P_w by UV–vis spectrophotometer (UV-1900, Holm & Halby, Denmark). Soil pH was measured using a pH meter (PHM220, Radiometer Analytical SAS, Lyon) in a soil suspension of 8 cm^3 of soil in 30 mL deionized water. Soil EC was measured using an EC meter (CDM210, Radiometer Analytical SAS, Lyon) in a soil suspension of 4 g soil in 36 mL deionized water.

2.3. Soil hydraulic properties and gas transport

To determine the soil water retention curve, the soil cores were saturated and drained step by step to − 3, −5, and −10 kPa, in sandboxes, and to −30 and −50 kPa in the pressure plate apparatus. At each matric potential, soil gas diffusivity (D_p) and soil air permeability (k_a, μm^2) were measured before proceeding to the next drainage step. Soil gas diffusivity was determined by the one chamber non-steady-state method (Taylor, 1950). The soil core was placed at the bottom of a chamber, with one side open to the atmosphere, allowing O_2 in the air to diffuse in the chamber through the soil core. The chamber was flushed with N_2 before the measurements and the change in concentration of O_2 with time was recorded for 2 h. The gas diffusivity of O_2 in free air (D_0) given as 0.205 $cm^2\ s^{-1}$ was used to scale D_p for the calculation of relative gas diffusivity (D_p/D_0). The detailed setup is described by Schjønning et al. (2013).

Soil k_a was measured by the Forchheimer approach. Compressed air at four different pressure values (5, 2, 1, and 0.5 hPa) was applied to the soil core in a chamber with one end connecting the atmosphere, and the airflow at each pressure was measured. The Darcian k_a was calculated from the Forchheimer polynomial regression using the four pressure and flow values. The detailed setup and the procedure are described by Schjønning and Koppelgaard (2017).

The K_{sat} was measured by the constant-head method according to Klute and Dirksen (1986). Briefly, the 100 cm^3 soil cores were first saturated with 0.01 M $CaCl_2$. Then the hydraulic head difference of 3.65 cm was kept on the samples for a maximum of 30 min, and the effluent was taken and recorded. K_{sat} (cm h^{-1}) was calculated as follows:

$$K_{sat} = \frac{W \times L \times 60}{\left(\left(\pi \times \left(\frac{d}{2}\right)^2\right) \times t \times \Delta H\right)} \tag{1}$$

where the w (g) is the weight of effluent, t (min) is the time, $d = 6.06$ (cm) is the diameter of the soil core, $\Delta H = 3.65$ (cm) is the difference of the hydraulic head, $L = 3.48$ (cm) is the length of the soil core.

After the measurements, the soil cores were oven-dried at 105 °C for 48 h to determine the oven-dried mass. The ρ_b (g cm^{-3}) was estimated as the ratio of oven-dried mass to the total volume of the soil core. The weight and volume of the stones > 2 mm in the soil cores were deducted in the calculation of ρ_b. The soil particle density (ρ_s) was estimated based on the clay and soil organic matter (SOM) content using the model given by Schjønning et al. (2017). The total porosity (ϕ, $cm^3\ cm^{-3}$) was calculated from ρ_b and ρ_s. Volumetric water content (θ, $cm^3\ cm^{-3}$) was calculated by multiplying gravimetric water content by ρ_b. The air-filled porosity (ε, $cm^3\ cm^{-3}$) was calculated as the difference between ϕ and θ. The equivalent pore diameter (d, μm) at each matric potential was calculated using the equation $d = -3000/\psi$, where Ψ is the matric potential (cm H_2O). To evaluate the effect of manure on different pore sizes, we defined micropores as pore sizes ≤ 30 μm whose volume was equivalent to θ at the matric potential of −10 kPa. The volume of pores > 30 μm, which was considered noncapillary porosity, was calculated from the difference between ϕ and microporosity.

To determine the water content at wilting point (−1500 kPa), field moist samples were passed through a 2 mm sieve and dried gradually. During the drying process, the water potential of the samples was measured continuously using the WP4-T dewpoint potentiometer (Decagon Devices, Inc., Pullman, WA, USA) until the values were above pF4.4 (~−2500 kPa). After the measurement, the water content at each drying step was calculated from the oven-dried mass (105 °C, 24 h). The θ and matric potentials between −1000 kPa to −10000 kPa were used to predict the θ at wilting point (−1500 kPa). The plant available water (PAW, $cm^3\ cm^{-3}$) equalled the difference of water contents at $\Psi = -10$ kPa and $\Psi = -1500$ kPa.

2.4. Water-stable aggregates

The WSA was determined on field-moist soil samples using the wet sieving method adapted from Angers et al. (2007). Five grams of field-moist aggregates (< 8 mm) were placed on a sieve with openings of 250 μm on a wet-sieving apparatus (Eijkelkamp, the Netherlands). The sieve was raised and lowered for 3 min (stroke = 1.3 cm, 34 times min^{-1}). The particles that remained on the sieve were dried at 105 °C for 24 h, followed by mixing with 0.002 M sodium pyrophosphate for 24 h to disperse aggregates. The weight of the fraction > 250 μm was obtained by sieving the suspension. The WSA was calculated from the stable aggregates that remained on the sieve and corrected with particles > 250 μm. Duplicate measurements were done for each plot.

2.5. Models

To describe the relationship between soil gas diffusion and air-filled porosity, a generalized macroporosity-dependent model (GMP) developed by Moldrup et al. (2000) and Deepagoda et al. (2011) for the comparison of different soils was evaluated for the dataset:

$$D_p/D_0 = 2\varepsilon^3 + 0.04\varepsilon \tag{2}$$

To further assess the soil pore structure and connectivity among different treatments for a given soil, the structure index P given by Kawamoto et al. (2006) that relates k_a and ε was used to characterise the soils:

$$P = \frac{k_a}{(2\varepsilon^3 + 0.04\varepsilon)} \tag{3}$$

Finally, to examine the effect of the manure application on pore structure (continuity, complexity, and distribution), we fitted a simple exponential model proposed by Marshall (1959) that relates D_p/D_0 and ε:

$$D_p/D_0 = m\varepsilon^{N_d} \text{ or } \log\left(D_p/D_0\right) = \log(m) + N_d\log(\varepsilon) \quad (4)$$

where m and N_d are fitting parameters. Because $D_p/D_0 = 10^{-4}$ is considered as zero diffusion in air-filled pore space, so the ε at that point was considered as diffusion percolation threshold (D_{PT}, m^3 m^{-3}), i.e., $D_{PT} = 10^{-[\log(m)+4]/N_d}$.

2.6. Statistics

Statistical analyses were conducted in R 4.0.5 (R Core Team, 2021). The Shapiro-Wilk test was carried out to check the data normality. One-way ANOVA was done to evaluate differences among the treatments. For a given field site, pairwise comparisons by the *Holm-Sidak* method was used to identify the significant difference between treatments ($p < 0.05$) using the "*pairwiseComparisons*" package (Patil, 2019). Due to the lack of field replicates in Bad Lauchstädt, all results from this site were excluded from the ANOVA analyses. The figures were drawn using "*ggplot2*" (Wickham, 2016). To compare the sites and the soil attributes among the three LTEs, principal component analysis (PCA) was performed on all three sites together and on the sandy site alone and in total 13 soil attributes were included, i.e., Clay, OC, TN, ρ_b, pH, EC, Mg, P_w, WSA, PAW and $k_{a,10}$, $D_{p,10}/D_0$, ε_{10} at $\Psi = -10$ kPa (indicated as a subscript). Root mean square error (RMSE) was calculated to evaluate the performance of the GMP model on the measured data:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(predicted_i - measured_i)^2} \quad (5)$$

where n is the number of measurements.

3. Results

3.1. Basic soil physicochemical properties

According to the USDA classification (Soil Science Division Staff (USDA-NRCS), 2017), the texture of Lanna, Bad Lauchstädt and Askov soils is silty clay (SiC), silty loam (SiL) and sandy loam (SL), respectively (Table 1). Thus, hereafter, the three LTEs are referred to as clayey site, silty site and sandy site, respectively. The SOC, TN and nutrient contents were higher in the plots with manure than UNF for all three sites. As shown in Table 1, in the clayey site, manure increased SOC and TN by 19% compared to UNF. In the silty site, manure ($\geq$ 30 t ha^{-1}) increased SOC by 36 – 48% and TN by 54 – 68%, and by 27 – 37% and 38 – 42% for the sandy site, respectively. Despite being BF for around two decades, the SOC and TN contents were not significantly different from the UNF in the clayey site. The addition of 37.5 t ha^{-1} manure in the sandy site led to drastic increases in P_w (~320 – 840 %), Mg (~50 – 120 %) and K (~145 – 225 %) and for the 30 t ha^{-1} manured silty site, the increases were P_w ~ 520 – 600 %, Mg ~ 50 – 100 % and K ~ 160 – 210 % compared to UNF.

Manure application led to average decreases in ρ_b of approximately 3 – 4 % in the sandy and clayey site, and 6 % in the silty site. The BF in the clayey site had a slightly lower ρ_b than UNF, albeit insignificantly. The sandy site at Askov was rich in gravel and the ρ_b values presented here were corrected for gravel contents. The ρ_b of gravel-free soil was around 92 – 99 % of the values with gravels (data not shown). The pH of originally acidic soil, i.e., the clayey and sandy sites, increased after manure addition and manure decreased pH for originally alkaline soil, namely, the silty site. The input of manure increased EC for the clayey and sandy sites, while the 20 t ha^{-1} manure rate did not increase EC in the silty site. In most cases, the two rates of manure in the silty and sandy sites had no significant differences in the SOC, TN, nutrients, pH and EC, and insignificant differences were also observed between the BF and UNF in the clayey site. As for the effect of the crop type, the maize plots had lower nutrient content, pH and EC, and higher ρ_b than the barley

Table 1
Soil textural class, clay and silt content, bulk density and other chemical properties at the three field sites. The order of the crops in Bad Lauchstädt and Askov in the table followed the crop rotation sequence order in the field.

Field	Crop	Treatment	Clay	Silt	SOC	TN	P_w	K	Mg	ρ_b	$pH(H_2O)$	EC
			g 100 g^{-1}				mg kg^{-1}	mg 100 g^{-1}		g cm^{-3}		dS m^{-1}
Lanna (Silty clay)	–	Bare fallow	41	47	1.9^{b}	0.17^{b}	11^{b}	17^{b}	27^{ab}	1.52^{a}	6.43	0.23^{b}
	W.wheat	Unfertilized	40	47	1.9^{b}	0.16^{b}	10^{c}	14^{b}	24^{b}	1.54^{a}	6.47	0.22^{b}
		38t FYM	40	46	2.3^{a}	0.20^{a}	12^{a}	28^{a}	31^{a}	1.48^{b}	6.60	0.29^{a}
Bad Lauchstädt (Silt loam)	Maize	Unfertilized	22	69	1.6	0.11	4	15	17	1.64	7.58	0.38
		20t FYM	21	67	2.0	0.15	19	22	22	1.58	7.14	0.38
		30t FYM	20	66	2.2	0.18	30	41	25	1.51	7.33	0.50
	Spring barley	Unfertilized	21	69	1.6	0.11	6	18	14	1.47	8.21	0.74
		20t FYM	20	68	2.0	0.15	21	40	24	1.34	7.85	0.62
		30t FYM	21	66	2.3	0.18	36	56	28	1.39	7.46	0.81
Askov (Sandy loam)	W.wheat	Unfertilized	9	18	1.1	0.09^{b}	2^{b}	6^{b}	4^{b}	1.46	6.33	0.18^{b}
		25t CSL	9	18	1.5	0.12^{a}	6^{ab}	15^{ab}	8^{a}	1.45	6.46	0.24^{ab}
		37.5t CSL	9	18	1.5	0.13^{a}	10^{a}	18^{a}	10^{a}	1.39	6.69	0.36^{a}
	Maize	Unfertilized	10	21	1.1	0.08^{b}	1^{c}	3^{c}	5^{b}	1.41	6.64	0.23
		25t CSL	11	22	1.3	0.11^{ab}	2^{b}	8^{b}	7^{a}	1.40	6.46	0.28
		37.5t CSL	10	21	1.5	0.12^{a}	5^{a}	10^{a}	8^{a}	1.40	6.59	0.30
	Spring barley	Unfertilized	10	21	1.1^{b}	0.08^{b}	1^{c}	4^{c}	4^{b}	1.54	6.55	0.16
		25t CSL	10	20	1.3^{a}	0.11^{a}	3^{b}	9^{b}	8^{a}	1.48	6.58	0.36
		37.5t CSL	10	21	1.3^{a}	0.11^{a}	5^{a}	11^{a}	9^{a}	1.49	6.58	0.26
	Grass/clover	Unfertilized	11	21	1.2^{b}	0.10	0.5^{c}	5^{b}	6^{b}	1.55^{a}	6.59	0.21
		25t CSL	10	20	1.5^{a}	0.13	2^{b}	10^{a}	8^{a}	1.47^{ab}	6.63	0.30
		37.5t CSL	10	20	1.6^{a}	0.14	4^{a}	12^{a}	9^{a}	1.44^{b}	6.98	0.41

FYM, farmyard manure; CSL, cattle slurry; 38 t, 38 t ha^{-1} 2 yrs^{-1}; 20 t, 30 t, 20 and 30 t ha^{-1} 2 yrs^{-1}; 25 t, 37.5 t, 25 and 37.5 t ha^{-1} yr^{-1}; SOC, soil organic carbon; TN, total nitrogen; P_w, water-extractable phosphorus; K, plant-available potassium; Mg, plant-available magnesium; ρ_b, bulk density; EC, electrical conductivity. The superscript letters indicate the significant difference between treatments within a field site ($p < 0.05$). Data without letters in silty clay and sandy loam sites indicate non-significant difference. Data from the silt loam site were excluded from the one-way ANOVA analyses due to the lack of field replicates.

plots on the silty site. On the contrary, the ρ_b of the maize plots in the sandy site was lower than for the other crop types.

3.2. Soil water retention and soil pore characteristics

At all considered matric potentials, the clayey site held more water than the other two sites (Fig. 1). The BF in the clayey site had slightly lower water content than the UNF, while the manure treatment had significantly higher water content than both BF and UNF (Fig. 1a). Likewise, the manure-treated soil had higher water content than UNF in the silty site and the barley and grass plots in the sandy site (Fig. 1b, c, f & g). The differences between manure treatment and UNF were more observable in the silty site than in the sandy site. Although the 30 t treatment had higher θ values than the 20 t treatment in the maize plots at water potentials ≤ -10 kPa (-3 to -10 kPa), there were very slight differences between the two rates of manure for the rest of the plots. The water retention behaviour also differed among the crops. Surprisingly, the 25 t treatment had significantly lower water retention than UNF in the wheat plots of the sandy site, and there were no significant differences between 37.5 t and UNF (Fig. 1d). The difference in water retention was not significant between manure treatments and UNF in the maize plots (Fig. 1e). Soil from the grass plots held more water than soil from the other three crops in the sandy site.

The clayey site was dominated by micropores with ~ 90 % of ϕ and the manured plots had the most micropores with 94 % of ϕ of which > 80 % was < 6 μm (Fig. S1). The majority of the pores in the silty site were also micropores. Around 86 % of ϕ were micropores in the manured maize plots in the silty site, and 78 % for UNF. In the barley plots, the values were 77 – 80 % for the manured barley field and 69 % for UNF. In the sandy site, around 65 – 70 % of ϕ were micropores in the grass plots, while in the other three plots, > 30 % of ϕ comprised pores > 100 μm.

Compared to the BF, vegetation slightly increased PAW, and there was no significant difference between manure-treated plots and UNF for PAW in the clayey site (Fig. 2a). Manure increased PAW for the silty site by ~ 50 % (Fig. 2b). The effect of manure on PAW in the sandy site interacted with the crop type. Manure significantly increased PAW for barley and grass plots by 26 – 36 % and 16 – 20 %, respectively, while decreasing it for wheat and maize plots by 17 – 27 % and 15 – 16 %, respectively (Fig. 2c). Among the four crop types, the grass field with history of manure addition had the highest PAW in the sandy site, being 0.20 $cm^3\ cm^{-3}$, followed by maize (0.16 $cm^3\ cm^{-3}$).

3.3. Gas transport and saturated hydraulic conductivity

In the clayey site, the BF plots had slightly higher D_p/D_0 than the manure treatment, and UNF had the lowest D_p/D_0 values (Fig. 3a). The effect of manure varied with crop in the silty and sandy sites. In the maize plots of the silty site, the D_p/D_0 was similar between UNF and manure treatments below $\Psi = -10$ kPa, above which the differences between the treatments increased (Fig. 3b). In the barley plots, UNF had 7 – 16 times higher D_p/D_0 than the 30 t in the barley plots (Fig. 3c).

For the sandy site, the D_p/D_0 values for wheat, barley and grass plots were within 0.003 – 0.06, while the range was much larger for the maize plots which was around 0.02 to 0.10 (Fig. 3d – g). There was a contrasting effect of manure on D_p/D_0 in the wheat, grass and barley plots. In the wheat and grass plots, the 37.5 t manure treatment had the highest D_p/D_0, while the UNF had the highest D_p/D_0 among the treatments in the barley plots. Similar to the silty site, the maize plots in the sandy site showed similar D_p/D_0 between manure treatments and UNF at the matric potentials below -10 kPa and the differentiation between treatments appeared when $\Psi > -10$ kPa.

The clayey site had a smaller range of ε than the other two soil types (Fig. 4). The manured plots had higher D_p/D_0 than UNF in the clayey site and the GMP model underestimated D_p/D_0 for the clayey samples (Fig. 4a). In the silty site, the maize plots, regardless of manure treatment, were less aerated than the barley plots at field capacity [-10 kPa] (Fig. 4b & c). In the barley plots, the data points separated into two groups, manured and UNF, and the GMP model well-described the manure treatments. By contrast, the maize plots in the sandy site were well aerated at $\Psi = -10$ kPa and had higher D_p/D_0 than the other three

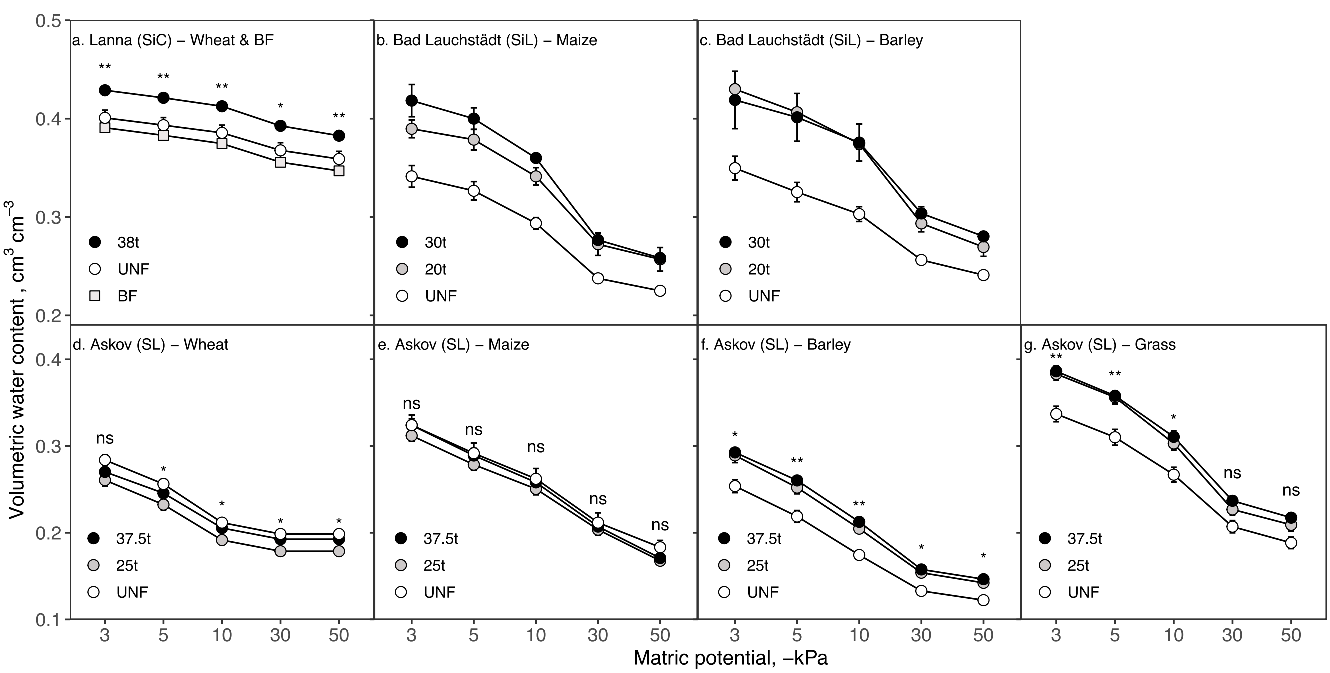

Fig. 1. Soil water retention curves of samples from the three sites at five matric potentials. SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 20 t, 30 t, 25 t, 37.5 t, 38 t indicate the tonne ha^{-1} of manure applied. Note the difference in the scales of the y-axes. The asterisk above the points indicates that there are significant differences between manure treatments and UNF. ns, non-significant; *, $p < 0.05$; **, $p < 0.01$. The error bars in the SiC and SL sites represent the standard error (SE) of field replicates. For the SiL site, error bars represent the SE of replicates within one plot, so the data were excluded from the ANOVA analysis.

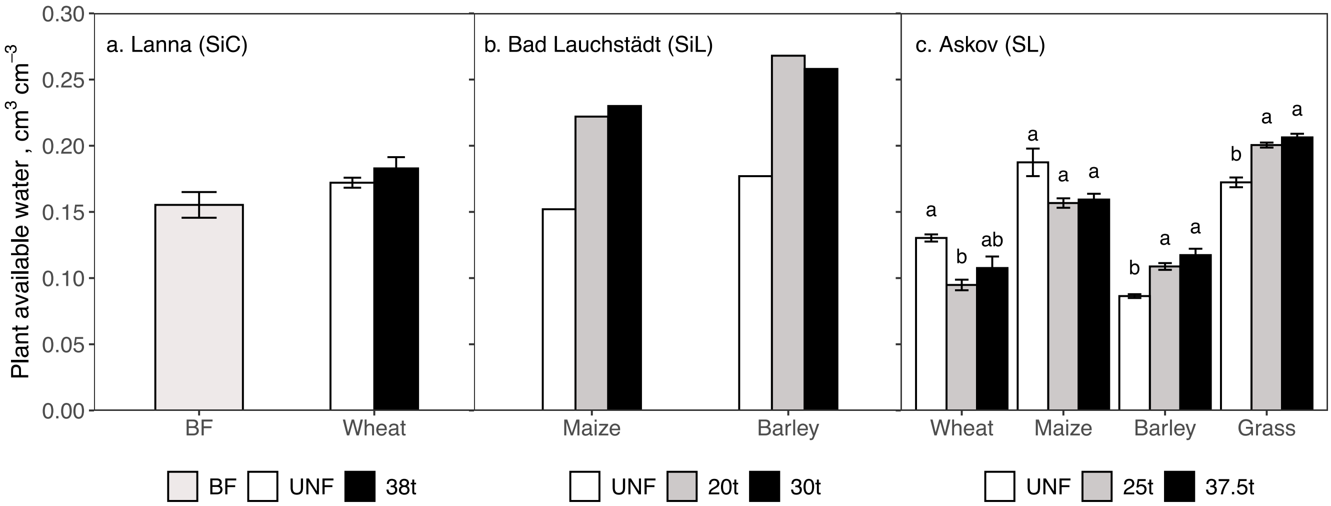

Fig. 2. Plant available water (PAW) content of samples from the three sites. SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 20 t, 30 t, 25 t, 37.5 t, 38 t indicate the tonne ha^{-1} of manure applied. The lowercase letters indicate the significant difference between treatments, $p < 0.05$. The bars without letters indicate no significant difference between treatments. The error bars in the SiC and SL sites represent the standard error (SE) of field replicates. For the SiL site, error bars represent the SE of replicates within one plot, so the data were excluded from the ANOVA analysis.

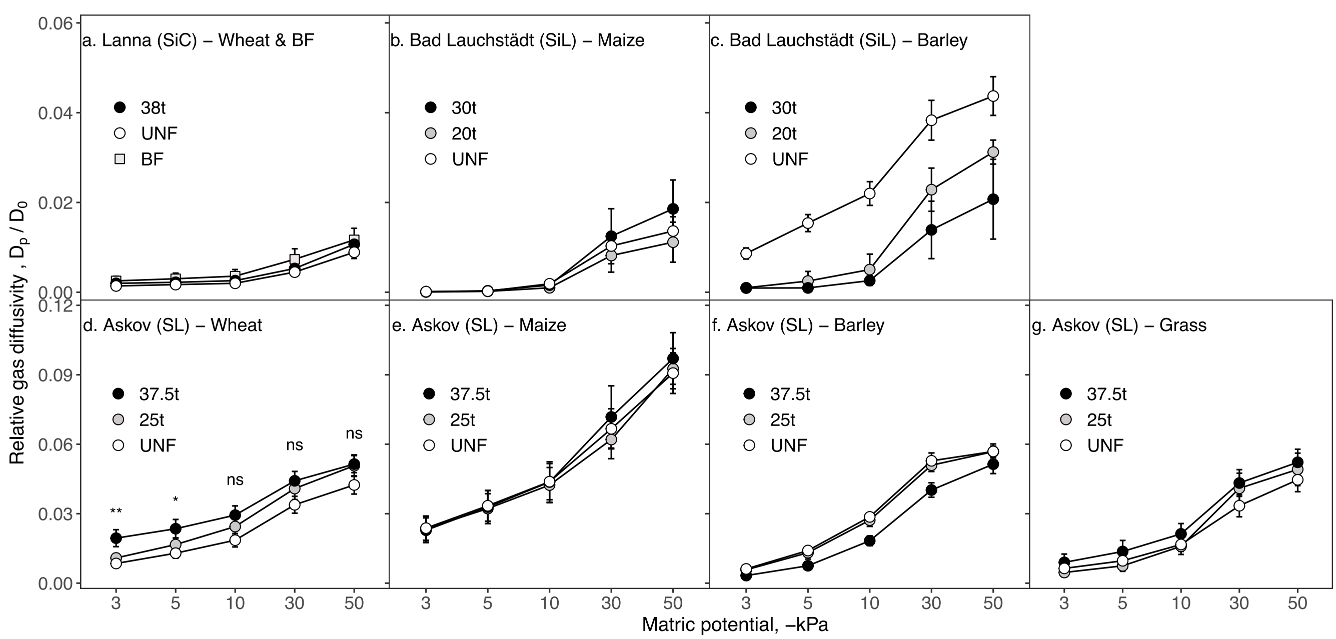

Fig. 3. Soil relative gas diffusivity of samples from the three sites at five matric potentials. SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 20 t, 30 t, 25 t, 37.5 t, 38 t indicate the tonne ha^{-1} of manure applied. Note the difference in the scales of y-axes. The asterisk above the points indicates that there are significant differences between manure treatments and UNF. ns or without labels in a, d – g, non-significant; *, $p < 0.05$; **, $p < 0.01$. The error bars in the SiC and SL sites represent the standard error (SE) of field replicates. For the SiL site, error bars represent the SE of replicates within one plot, so the data were excluded from the ANOVA analysis.

plots (Fig. 4d – g; Table 2). At field capacity, the D_p/D_0 for the grass plots was smaller than that for other plots (Table 2). There was no clear difference between manure treatments and UNF for all crops in the sandy site.

Schjønning et al. (2003) suggested thresholds of D_p/D_0 for optimum aerobic microbial activity, which was 0.025 for the sandy site and 0.005 for the fine-textured site. Based on these thresholds, the fine-textured (clayey and silty) sites will most likely not be able to provide sufficient air for aerobic microbial activity at field capacity, whereas the majority of the maize plots data in the sandy site at field capacity were above that threshold, and most are below the threshold in the grass plots (Fig. 4e & g). The effect of manure on k_a for different plots showed similar trends as that of D_p/D_0 apart from the maize plots in the silty site and the sandy grass plots (Fig. S2).

In Fig. 5, the structure index P, with threshold values of 100, and 1000 were used to characterise the soil pore structure status. Soils that place above P = 1000 are considered well structured whereas those below P = 100 are considered poorly structured. Most plots were above P = 100 with a few exceptions (Fig. 5). Despite having much lower ε values, the range of k_a for the clayey site was close to that for the sandy site. The silty site had lower k_a than the other two sites at a given ε. The clayey site had the most values above P = 1000, including most values at the field capacity, and some of the BF soils had much higher P values than the cropped plots (Fig. 5a).

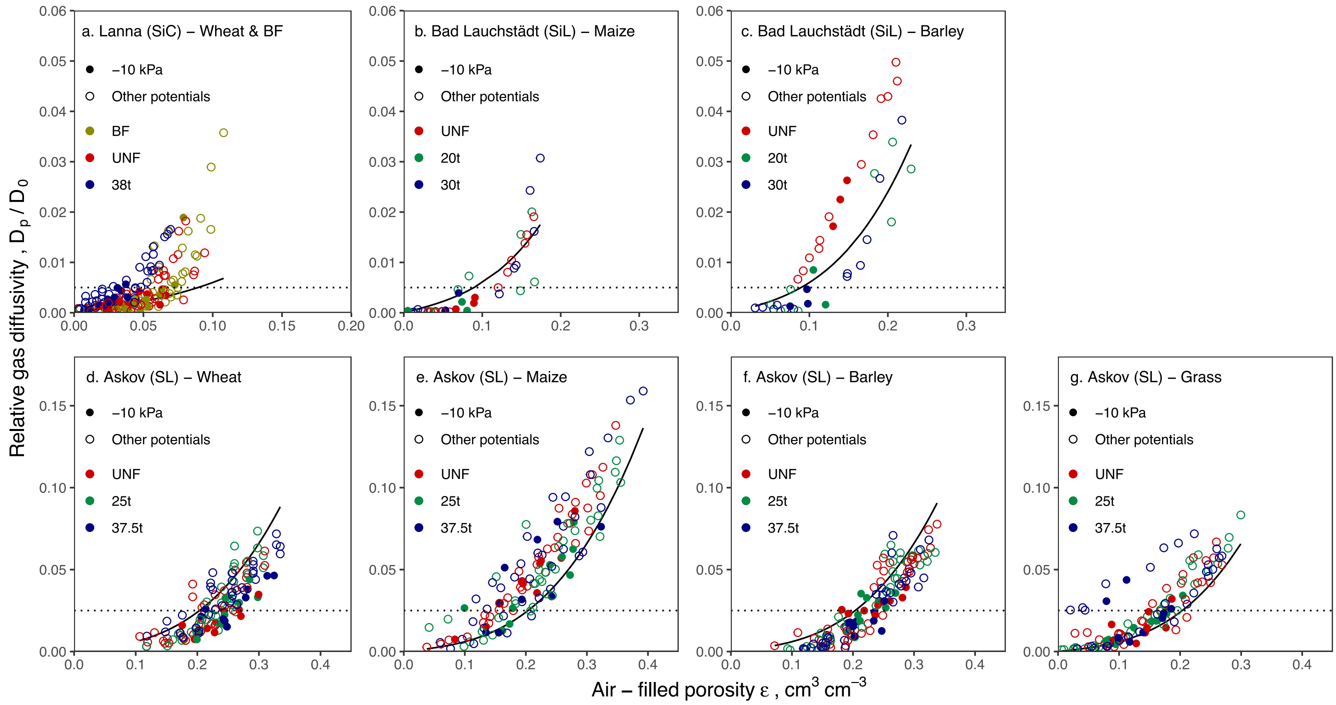

Fig. 4. Relative gas diffusivity as a function of air-filled porosity for all experimental plots. The matric potential denoted "Other potentials" includes the potentials of −3, −5, −30 and −50 kPa. The solid lines are the GMP model $D_p/D_0 = 2\varepsilon^3 + 0.04\varepsilon$ (Moldrup et al., 2000). The horizontal dotted lines are the gas diffusivity threshold for optimum aerobic microbial activity. SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 20 t, 30 t, 25 t, 37.5 t, 38 t indicate the tonne ha^{-1} of manure applied. Note the difference in the scales of axes.

Table 2
Soil relative diffusivity (D_p/D_0) and air permeability (k_a) at Ψ = −10 kPa and estimates of the diffusion percolation threshold (D_{PT}, set at $D_p/D_0 = 10^{-4}$), slopes of log–log plots of relative gas diffusivity vs air-filled porosity (N_d), and saturated hydraulic conductivity (K_{sat}). SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 38 t, 38 t ha^{-1} 2 yrs^{-1} farmyard manure; 20 t, 30 t, 20 and 30 t ha^{-1} 2 yrs^{-1} farmyard manure; 25 t, 37.5 t, 25 and 37.5 t ha^{-1} yr^{-1} cattle slurry. The standard error (SE) in brackets represents the SE of the field replicates for SiC and SL sites, and the SE of the replicates from one plot for the SiL site.

Field	Crop	Treatment	k_a	D_p/D_0	N_d	D_{PT}	K_{sat}
			μm^2	×10^{-3}		m^3 m^{-3}	cm h^{-1}
Lanna	–	BF	66 (55)	3.6 (1.5)	1.69	0.013	32 (27)
(SiC)	W.wheat	UNF	14 (5)	2.0 (0.3)	1.15	0.039	7.5 (4.0)
		38t	27 (10)	2.6 (0.5)	1.03	0.011	15 (6)
Bad Lauchstädt	Maize	UNF	0.2 (0.04)	1.9 (0.7)	3.17	0.018	0.1 (0.1)
(SiL)		20t	0.1 (0.1)	1.0 (0.6)	1.42	0.106	0.1 (0.1)
		30t	0.3 (0.2)	1.6 (1.2)	1.45	0.048	0.3 (0.3)
	Spring barley	UNF	22 (6)	22 (2.6)	2.10	0.009	8.3 (4.1)
		20t	2.1 (1.8)	5.0 (3.4)	2.67	0.023	0.5 (0.3)
		30t	1.1 (0.5)	2.6 (1.1)	2.07	0.030	0.6 (0.5)
Askov	W.wheat	UNF	48 (19)	19 (2.9)	2.36	0.027	41 (27)
(SL)		25t	38 (7)	24 (3.8)	3.43	0.029	21 (6)
		37.5t	148 (61)	29 (4.0)	2.09	0.022	101 (40)
	Maize	UNF	182 (50)	44 (7.8)	1.87	0.009	126 (36)
		25t	202 (52)	42 (7.6)	1.51	0.009	171 (43)
		37.5t	230 (70)	44 (8.7)	2.08	0.011	215 (69)
	Spring barley	UNF	64 (20)	29 (1.8)	2.44	0.026	43 (19)
		25t	39 (15)	27 (2.7)	3.44	0.028	52 (48)
		37.5t	20 (8)	18 (2.1)	3.80	0.031	4.0 (1.0)
	Grass/	UNF	79 (51)	17 (3.0)	1.46	0.013	46 (32)
	clover	25t	28 (22)	16 (3.5)	1.32	0.011	48 (37)
		37.5t	251 (193)	21 (4.5)	1.07	0.008	237 (160)

In the silty site, the maize plots had smaller k_a than the barley plots, ranging from 0 to 3.5 μm^2, with a few points being 0 at low ε and most points from the maize plots, including the ones at the field capacity, were below P = 100 (Fig. 5b & c). The UNF of barley plots was above P = 1000 while the manure treatments were below it. It can be concluded that the structure of the soil in the maize plots was not as developed as that of the barley plots which were medium developed.

For the sandy site, the maize plots had the most points above P = 1000 and the other plots fell into the zone between P = 100 and P = 1000 (Fig. 5d – g). The variation of k_a in the grass plots was larger than in the other plots, while the wheat plots seemed to have a relatively more homogenous structure, with most points concentrated around P = 1000 (Fig. 5d; Fig. S2). At field capacity, the values of k_a were larger in the maize plots than in the other plots (Table 2). The K_{sat} was positively correlated to k_a at the field capacity (correlation coefficient = 0.8, R^2 = 0.84).

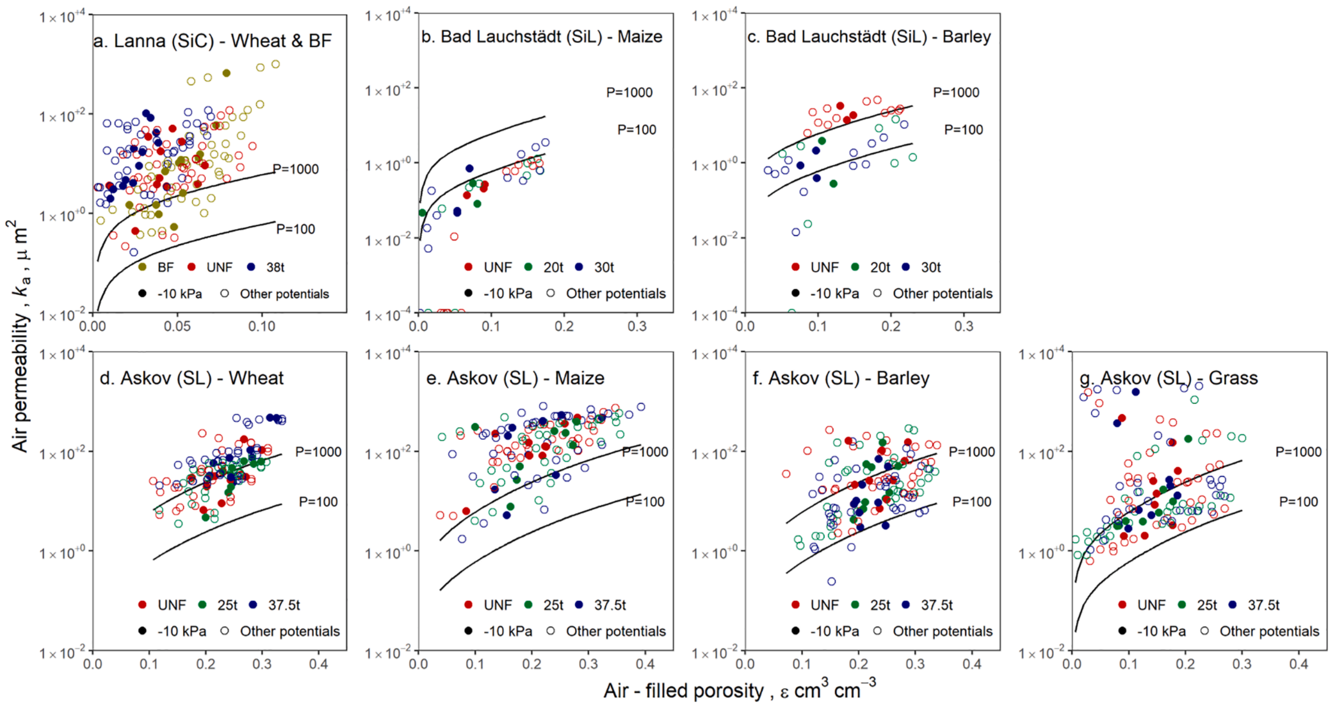

Fig. 5. Air permeability as a function of air-filled porosity for all plots. The matric potential denoted "Other potentials" includes the potentials of −3, −5, −30 and −50 kPa. The lines are the model $k_a = P(2\varepsilon^3 + 0.04\varepsilon)$ (Kawamoto et al., 2006). SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 20 t, 30 t, 25 t, 37.5 t, 38 t indicate the tonne ha^{-1} of manure applied. Note the difference in the scales between the SiL site and the other two sites.

The exponential model (Equation (4)) fitted the data well for the silty and sandy sites, while slightly inadequate for the clayey site (Fig. S3). The intercepts of the regression lines at $D_p/D_0 = 10^{-4}$ represented the percolation threshold, D_{PT}, which was the estimate of ε that was excluded from the gas diffusion process. The slope of D_p/D_0 vs ε, i.e., N_d, describes the change of D_p/D_0 with a changing ε, the higher the value, likely the more complex the structure. Neither the N_d nor D_{PT} values showed a clear pattern of variation with manure application (Table 2). The crop type tended to have a major impact on N_d and D_{PT} for a given soil type.

3.4. Water-stable aggregates

The clayey site had a higher proportion of WSA than the other two soil types (Fig. 6) and the highest value was for the 38 t treatment, i.e., 0.94 ± 0.001 (Fig. 6a). A similar trend was also observed in the barley plots in the silty site, where the 30 t treatment exhibited the largest WSA value (0.92 ± 0.001). Surprisingly, manure lowered WSA for the maize plots in the silty site, from 0.89 ± 0.019 for the UNF to 0.74 ± 0.002 for the 30 t treatment (Fig. 6b). The positive effect of manure on WSA could be seen at the sandy site, although the effect was not significant (Fig. 6c). The UNF of the grass plots in the sandy plots had the highest WSA (0.89 ± 0.041) than the UNF under the other three crops.

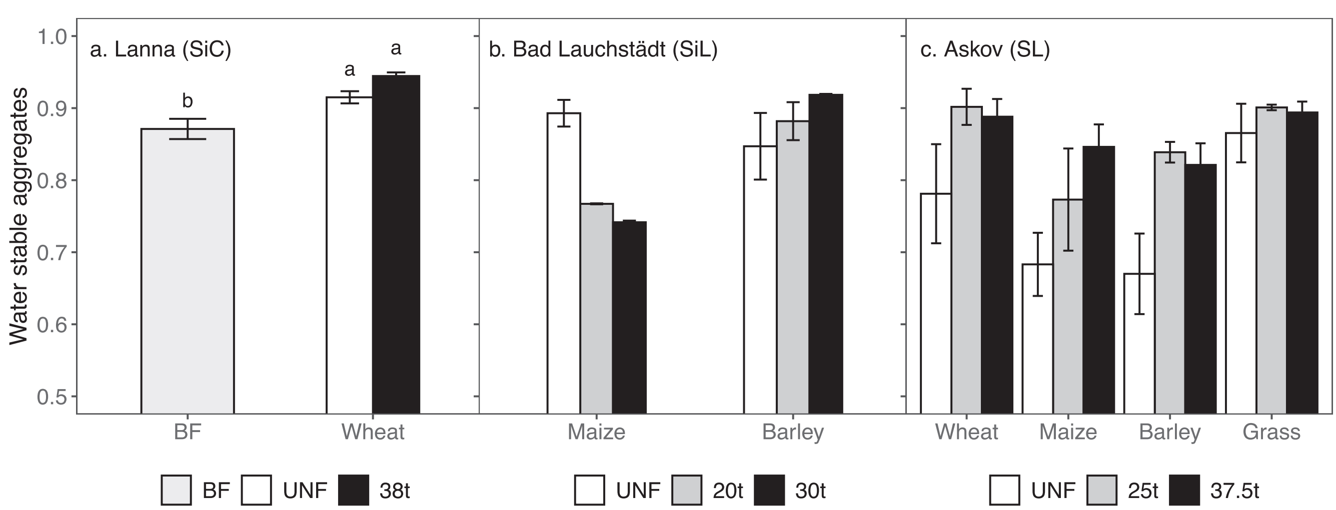

Fig. 6. Water stable aggregates (WSA) for the three sites. SiC, silty clay; SiL, silt loam; SL, sandy loam; BF, bare fallow; UNF, unfertilized; 20 t, 30 t, 25 t, 37.5 t, 38 t indicate the tonne ha^{-1} of manure applied. The lowercase letters indicate the significant difference between manure treatments, $p < 0.05$. The bars without letters indicate no significant difference between treatments. The error bars in the SiC and SL sites represent the standard error (SE) of field replicates. For the SiL site, error bars represent the SE of replicates within one plot, so the data were excluded from the ANOVA analysis.

3.5. PCA analyses

The first, second and third components explained 50 %, 19 % and 10 %, respectively, of the variation in all the plots (Fig. S4). The fine-textured sites and the sandy site were separated along PC1 and the crop type was slightly differentiated along PC2. The OC, TN and Mg had high loadings in PC1, EC, pH and ρ_b in PC2 and the structural property $k_{a,10}$ had a high loading in PC3. The pH and EC distinguished the silty site from the other two soil types and the ρ_b separated the clayey site from the silty site. Because the soil texture of the three sites was distinct from one another, the effect of texture can mask the effect of manure and crop types. Therefore, the PCA in Fig. 7 was done on the sandy site alone. The PC1 explained 34 %, PC2 21 % and PC3 explained 19 % of the variance. The OC, TN and Mg had high loadings in PC1 and the $D_{p,10}/D_0$, $k_{a,10}$ and ρ_b had high loadings in PC2. The ε_{10} and PAW had high loadings in PC3 and PH and EC in PC4 (9 %). The amount of manure was distributed along PC1 and the maize and grass plots were separated along PC2. The maize plots can be separated from the other plots based on the structural properties including $D_{p,10}/D_0$, $k_{a,10}$, ε_{10} and ρ_b.

4. Discussion

The study hypothesized that the addition of manure would improve soil hydraulic and structural properties, and this improvement would be larger in the sandy site relative to the silty and clayey sites. Additionally, that the crop type would significantly influence how manure altered the soil properties. To test the hypotheses, we first discuss our results for each LTE separately, compare the improvements across the three sites and evaluate the effect of crop type in the silty and sandy sites.

4.1. Effect of long-term manure application

4.1.1. The clayey site

Long-term manure application enriched soil C, N and other nutrient pools in the clayey site and the high SOC contributed to a less dense soil in the manured plots than in the UNF. The ρ_b of BF was not significantly different from UNF (Table 1) and it might be because of the land use before the conversion to fallow. Barré et al. (2010) reported on the ρ_b of seven long-term BF sites and showed that sites with arable history had little change in ρ_b several decades after conversion to BF. The liming effect from the manure and the salts contained in the manure increased soil pH and EC, respectively (Ozlu and Kumar, 2018; Whalen et al., 2000). Despite the absence of manure, the BF retained more nutrients than UNF possibly because of the lack of nutrient uptake from plants. This is in contrast to the results reported by Yläranta et al. (1996) where around twofold K and Mg leached in the fallow clay compared to the barley clay lysimeter without irrigation, although, in agreement with our results, there was no difference in soluble phosphorus leaching in these two lysimeters.

The preservation of SOC in the BF, despite the absence of fresh

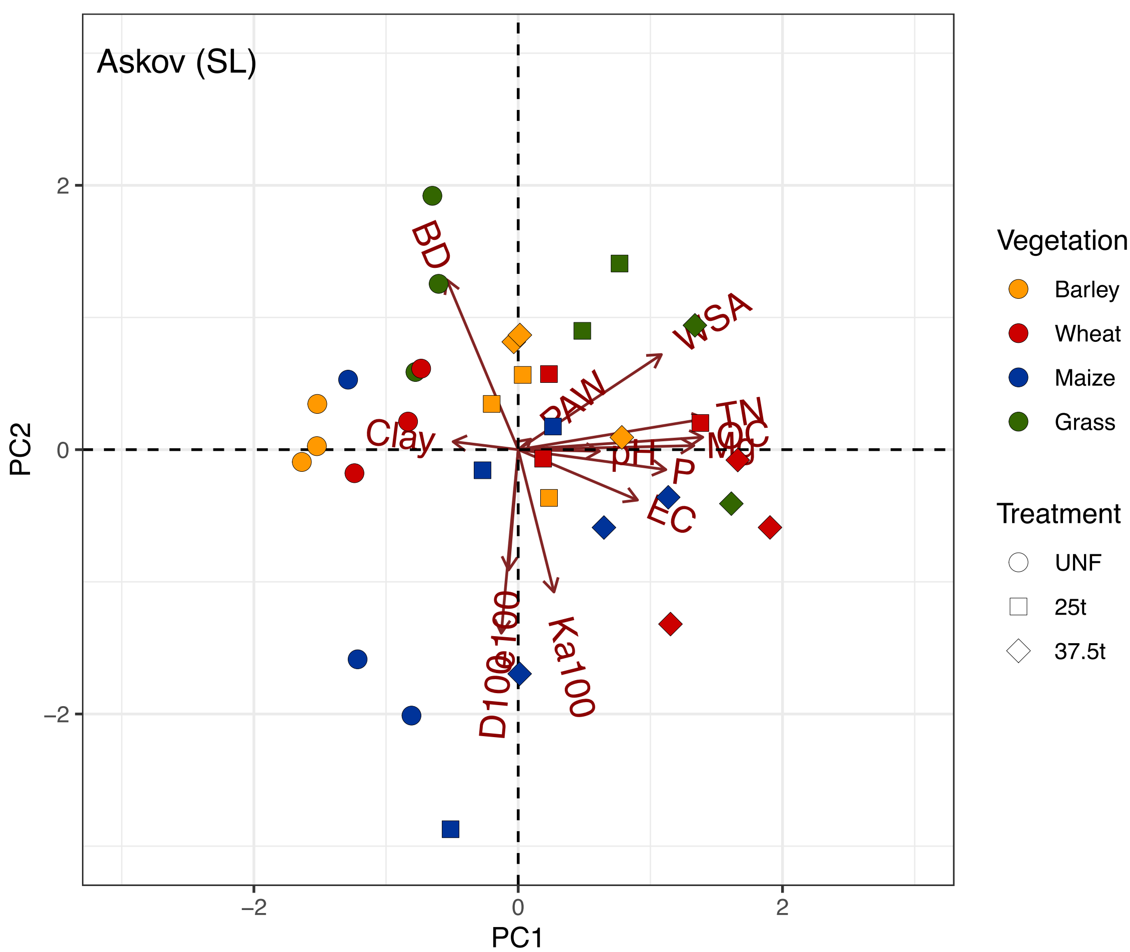

Fig. 7. Principal component analysis of soil basic and structural properties for the sandy loam (SL) site. BD, bulk density; OC, organic carbon; EC, electrical conductivity; e100, Ka100, D100, indicate air-filled porosity, air permeability, gas diffusivity at Ψ= –10 kPa, respectively; Mg, plant-available magnesium; P, water-extractable phosphorus; PAW, plant available water; TN, total nitrogen; WSA, water-stable aggregates; UNF, unfertilized; 25 t and 37.5 t indicate the tonne ha^{-1} of manure applied.

organic matter input for two decades, is likely due to the high contents of clay and silt in this site which provide physical or chemical protection of C from mineralization (Six et al., 2002). Although UNF had approx. 0.5 t ha^{-1} mean annual carbon input from roots and stubble (Kätterer et al., 2014), there seemed to be no accumulation of SOC in the UNF plots compared to BF. The higher values of OC and TN in the BF than in UNF were also observed in a silty clay loam loess soil by Yang et al. (2012). The deposition and upward movement of N were given by the authors as possible reasons for the high constant TN values in fallow plots. Furthermore, harrowing for weed control and the absence of soil cover in the BF facilitates evaporation, which may have prevented nutrients from leaching down the soil profile (Yang et al., 2012).

High SOC often results in higher porosity, especially macroporosity and cropped soil is expected to have higher porosity than BF (Naveed et al., 2014; Zaffar and Lu, 2015; Bacq-Labreuil et al., 2021). In this study, the pores > 30 μm were less affected by manure than the microporosity, and BF had more pores > 30 μm possibly due to the ploughing and the lack of plant roots that modify pore structure. The high amount of micropores in the cropped plots, especially the manured plots (Fig. S1), enabled the soil to retain more water than UNF, and potentially provide more water for plants (Fig. 2a). On the other hand, the water in the pores can block the gas flow pathways causing slightly lower gas diffusivity in the cropped plots (Fig. 3a). At field capacity, gas diffusion may be too low to provide sufficient O_2 for aerobic activity, especially for the cropped plots (Fig. 4a). This can be beneficial for C protection (Keiluweit et al., 2017), given the relatively high annual precipitation in the area.

Although high SOC is expected to produce soils that have high tortuosity and a more complex structure (de Jonge et al., 2009; Fang et al., 2021), the manured plots seemed to have a less complex structure than UNF as concluded from the low D_{PT} values (Table 2). The D_{PT} is considered as the threshold ε above which gas diffusion occurs in soil. The low D_{PT} values at this site indicate that more active air-filled pores contributed to the diffusion process, hence a less complex structure. Low values of N_d indicate little changes of D_p/D_0 when ε changes and it may be related to low soil complexity (Schjønning et al., 2002). However, Arthur et al. (2013) argued that the diffusion process depends on all air-filled pores involved rather than connected macropores and the N_d may not be a good indicator of soil pore complexity. The results were consistent with the findings from the LTE in Rothamsted, which revealed that FYM increased porosity and permeability than UNF for clay loam soil, and manured soil was less tortuous than UNF (Zhang et al., 2021). The high D_p/D_0 and k_a of BF at high ε may suggest a larger fraction of well-connected pores in the BF than in the cropped plots (Fig. 4a; Fig. 5a). This assertion is confirmed by the trends in K_{sat} as discussed below.

The larger K_{sat} of BF than the manured plots may indicate preferential flow in BF (Table 2), which may be caused by harrowing, and may explain the higher N_d and lower D_{PT} values for BF compared to UNF and the manured plot. The K_{sat} was twofold lower in UNF than in the manured plots, which may suggest less connected pores, as indicated by the higher D_{PT} value of UNF than the 38 t manure. Miller et al. (2002) reported increased field K_{sat} and water retention after 24 years of applying cattle manure 30 – 90 t ha^{-1} to clay loam soil. Likewise, Bhattacharyya et al.(2007) reported that after 8 years of 10 t ha^{-1} of manure application in silty clay loam soil in India, higher K_{sat} was observed in the manured field than in the control.

The smaller WSA in BF can be attributed to the absence of plants which leads to fewer soil binding agents originating from plant roots and the enmeshment by root hair (Materechera et al., 1994). This is plausible since the smaller WSA in the BF is despite the BF and UNF having identical levels of SOC. The increase of WSA by manure application has been reported by many studies. For example, Ozlu and Kumar (2018) found increased WSA in the top 10 cm of soil in two 12-year manure-treated silty loam sites in South Dakota, USA. Moreover, Aoyama et al. (1999) reported that an 18-year application of 20 t ha^{-1} manure resulted in higher SOC and favour of the formation of slaking-resistant macroaggregates (250 – 1000 μm). Their findings were confirmed in this study, despite the insignificant increase in WSA between UNF and manure treatments.

4.1.2. The silty site

The manure treatments had higher SOC, TN and nutrients and less dense soil (commensurate with the manure rate) than the UNF. For two silty loam soils and three levels of manure, similar increases in SOC, TN and WSA with manure rate were also reported by Ozlu and Kumar (2018). The silty site was originally alkaline and the addition of manure lowered the pH, probably because of organic acids in manure (Liang et al. 2012). However, there was no consistent pattern in the change of pH and EC between the 20 t and 30 t treatments (Table 1). The crop type and the difference in the manure application time may be two reasons for the inconsistency, which may be a consequence of the uneven distribution of roots and the decomposition of manure.

The two rates of manure showed a similar ability to retain more water and more PAW than UNF (Fig. 2b). Our results are similar to the results reported by Eden et al. (2012) and Naveed et al.(2014) on Bad Lauchstädt samples where two rates of manure had little difference in water retention and were higher than UNF. The addition of manure indeed improved water holding capacity, however, there was no consistent effect on the gas transport properties. In the barley plots, higher k_a at a given ε in UNF suggested that the pore connectivity was higher in UNF than in the manured plots and the soil pore structure of UNF was more developed than that of manured plots (Fig. 5c & S2). It may be explained by the high ρ_b of UNF. The denser soil in UNF had lower ϕ, more pores > 30 μm (Fig. S1) and held less water, which could lead to less water blockage of the gas pathway. de Jonge et al. (2009) presented the conceptual model describing that low-C soil may have a "downpipe-like pore system" that is dominated by continuous pores > 30 μm allowing higher convective airflow.

The soil in all three treatments in the maize plots was much denser than in the barley plots, had poorly developed structure, and had less stable aggregates in the manured treatments (Table 1; Fig. 5; Fig. 6). Additionally, the difference in structure between the treatments seemed indistinguishable in the maize plots (Fig. 5b). Nevertheless, UNF in both plots had lower D_{PT} than the manure treatments, suggesting more active pores in UNF. However, our results are contrary to the results reported by Naveed et al. (2014) who found the lowest D_p/D_0 and k_a in UNF at $\Psi = -10$ kPa and the highest macroporosity in the 30 t treatment.

Likewise, compared to our study, Eden et al., (2012) found opposite trends in K_{sat} among the treatments in the same experimental site. Although the authors claimed that K_{sat} did not reveal the structural difference in their study, the highest K_{sat} was found in the 30 t treatment. The difference between the results in this study and the reported results may be attributed to the crop type – Eden et al. (2012) took samples in the winter wheat growing season. The low K_{sat} in the maize plots and the manured barley plots can potentially cause waterlogging during rainfall events and less water infiltrating the root zone, which can limit crop yield despite the high PAW in the manured plots (Keller et al., 2012). The reasons for the surprisingly adverse effect of manure on WSA observed in the maize plots are not immediately obvious.

4.1.3. The sandy site

The higher SOC and other nutrients and the increase in EC also occurred in the manure-treated plots in the sandy site. The change in pH seemed to vary with crop types or the plots. A study done by Azeez and van Averbeke (2012) showed that the liming effect was gradually eliminated after manure was incorporated into sandy clay loam soil while manure-induced salinization was more long-lasting. This may explain the inconsistency of pH between treatments across different plots. Two manure rates seemed to make no significant difference in improving nutrient pools (Table 1). The liming practice in the field may also complicate the effect of manure on soil pH. Manure improved water retention and PAW in only the barley and grass plotss (Fig. 2c). It is partially consistent with the results reported by Blanco-Canqui et al. (2015) where they found manure induced higher water retention and available water in sandy loam soil. The PAW is estimated from water retained at field capacity and wilting point, and manure-induced increment in SOC resulted in an increase of water content at both matric potentials. Consequently, PAW did not always increase after manure application. The PAW mainly depends on pore size distribution (Haynes and Naidu, 1998). The volume of pores > 30 μm and microporosity varied with crops and manure rates in this study (Fig. S1). Manure had a little or negative effect on water retention in the wheat and maize plots, hence the little difference in porosity and the opposite trends of PAW from the other two plots.

The impact of manure on gas transport also varied. There was no general pattern in the effect of manure on gas transport. The manure treatments increased the porosity in the barley and grass plots with more proportion of micropores. However, there was no clear relationship between the complexity of soil pore structure and the amount of manure in these two plots (Table 2). The impact of manure on barley and grass plots may be related to the presence of grass in both plots. Schjønning et al. (2002) showed that air diffusion at a given ε was higher from the field without manure and ley than from a dairy farm in a sandy loam soil in Denmark. Contrary to their results, there was no distinguishable separation between manure treatment and UNF for gas diffusion vs ε in this study (Fig. 4d – g). In agreement with the trends reported by Schjønning et al. (2005), the 37.5 t had higher k_a than UNF, except for barley plots (Fig. S2).

Kawamoto et al. (2006) found P values equal to 700 for the loamy soils in Denmark while Arthur et al. (2012) reported P = 3500 for sandy loam soil. In this study, the values seemed close to 1000, except for the maize plots which fell above P = 1000 (Fig. 5d – g). It seems the effect of crop type overrode the effect of the manure treatment. The effect of manure on the pore structure was not clear, even though 37.5 t ha^{-1} manure tended to enhance WSA and K_{sat}, except for the barley plots. The root properties and the management of different crops may play an important role rather than manure solely, which will be discussed in a subsequent section.

4.1.4. Across the sites

Based on our hypotheses, we expected that any observed improvements in the soil properties would be larger in the sandy sites than in the silty and clayey sites. However, our hypotheses were refuted by the results. First, the accumulation of nutrients from the manure addition was more drastic in the silty site than in the sandy site, which might be due to the high SOC of the silty site and/or leaching in the sandy site. The small increment in nutrients in the clayey site may be attributed to its shorter experimental time than the two other LTEs or the smaller relative contribution to the previously present amount of nutrients. The manure seemed to have the opposite effect on pH, and it decreased the pH of the alkaline soils and increased the pH of acidic soils. The effect of manure rate on pH, EC and nutrient enrichments seems to be more pronounced in the silty soil than the sandy soil. The results from the LTE Box Plot Experiment Großbeeren also showed that manure combined with NPK increased SOC more in silty soil than in sandy soil (Körschens et al., 2013). The difference in the manure form in the two sites, i.e. FYM versus slurry, may also contribute to the different effects of manure on the properties.

Manure improved water retention and alleviated the compaction in all three sites as expected (Blanco-Canqui and Benjamin, 2013). However, the effect of manure on the hydraulic and gas transport properties varied with the texture and crop type, and the manure rate had very little effect. Because of the intrinsic difference in soil texture, the clayey and silty sites had more micropores than the sandy site. Thus, at −10 kPa, the anaerobic microbial activity was more likely prevalent in the fine-textured sites. The gas diffusion is in general higher in soil with low ρ_b than with high ρ_b (Stirzaker et al., 1996), and the clayey soil had the highest ρ_b in this study, thus the lowest D_p/D_0 (Fig. 3). Although there was no clear difference between UNF and manure treatment in D_p/D_0 vs ε for most plots, the GMP model tended to underestimate D_p/D_0 at a given ε for the clayey site and overestimate the data for the sandy site and it could be attributed to the difference in ρ_b (Fig. 4). Deepagoda et al. (2011) reported the tendency of the GMP model to underestimate data for dense soil and overestimate for light soil. The authors explained that dense soil had fewer water bridges between solid particles because of higher solid content at the same ε, thus lower tortuosity and higher D_p/D_0. Fujikawa and Miyazaki (2005) reported similar results while they attributed the difference to the pore shapes. They illustrated the effective space and ineffective space in the diffusion process and argued that compaction or dense soil might have caused the reduction in the latter and the increase in the former. As mentioned above, D_p/D_0 is the measurement of the diffusion process and involves all pores, while k_a is the measurement of convective movement and can provide information about changes and differences in soil pore structure, such as pore connectivity (Arthur et al., 2013; Moldrup et al., 2001). Despite the much lower range of ε in the clayey site than in the other two sites, the k_a of the clayey site was comparable to the other two sites, even higher than the silty site at a few points (Fig. 5). The pore structure of the clayey soil was well developed, while the silty soil seemed to be less developed. Similarly, the silty site had more inactive pores than the other two sites (Fig. S3; Table 2), and it also reflected on the K_{sat} (Table 2). The low K_{sat} of the silty site might be related to its high pH and EC (Candemir and Gülser, 2012). Lal (2020) summarized the relationship between SOC and water retention and concluded that the increase in SOC increased PAW for all soil types as the increase in water content at the field capacity was higher than at the wilting point. It held for most plots in this study, apart from the maize and wheat plots in the sandy site. The inconsistency in results may be also attributed to the small number of samples per plot.

The soil water retention, gas transport and hydraulic properties determined are very important for SOC decomposition (Kravchenko and Guber, 2017; Tecon and Or, 2017). Shakoor et al., (2021) reviewed the effect of manure, soil attributes and crop types on greenhouse gas (GHG) emissions for agricultural soils. They found that fine-textured soils (silty loam and silty clay) had the highest CO_2 emission, and the manure rate had a great impact on GHG emissions. The anaerobic condition in the silty loam soil favoured the production of CH_4. The manure rate shall be calculated carefully when implemented in real farms, considering the GHG emission control and the improvement of soil structural and hydraulic properties, given that manure rate had little effect on those properties in this study.

4.2. Effect of crop type

As we hypothesized, the effect of manure interacted with crop type in the silty and sandy sites with multiple crops. Although the silty and sandy sites were rotated with the same elements within each site every year, the crop type still had a different impact on the soil properties. From the PCA analysis, manure had a major impact on the measured properties and crop type influenced physical properties. In the sandy site, because of the dominant pores > 30 μm in the cereal plots, although the water content decreased with the water potential, the k_a changed little with the changing water potential (Fig. S2). Nevertheless, more open pores during the drying process resulted in higher D_p/D_0 (Fig. 3). The soil can most likely provide sufficient O_2 for aerobic activity in the cereal plots than in the grass plots at field capacity (Fig. 4d – g). The crop type differentiated the structural and hydraulic properties in the sandy site, especially between the maize, grass and the other two plots (Fig. 7). The barley and wheat plots had 3 times more inactive pores (~3%) in diffusion than the grass and maize plots (~1%) (Table 2) and they also had denser soil than grass and maize (Table 1). The grass had a great amount of belowground biomass and the dense roots can enmesh the soil, causing more stable aggregates and more micropores (Fig. 6; Fig. S1). The biological activity was visibly higher in the grass plots than in the other plots, leading to the preferential flow and high variation in k_a (Table 2; Fig. 5g & Fig. S2). Riley et al. (2008) also found higher earthworm density in crop systems with grass/ley.

More water was held in the pores in the grass plots and thus fewer pores for gas diffusion. The high C input and insufficient O_2 for aerobic microbial activity led to the accumulation of C in the grass plots. It should be noted that the accumulated C may not be preserved for the long term. Continuous loss of C has been observed in this LTE in the past century regardless of the management (Christensen et al., 2019). Kreba et al. (2017) reported higher gas diffusion, air permeability and pore continuity in the red clover dominant pasture system than wheat/maize crop system. Schjønning et al. (2002) found little difference in a comparison between crop systems with or without grass/ley. The effect of grass-clover on soil structural and hydraulic properties seemed dependent on the duration of grass/clover in the field. Riley et al. (2008) also reported that a longer period of grass/ley in the field helped maintain the good soil pore structure. Albeit the slight heterogeneity of the plots, the effect of grass on the soil pore structure did not seem to last long and was reshaped by the following crop wheat, which could be attributed to the ploughing (Fig. 1d & g; Fig. 5d & g). Ploughing destroyed the old pore structure and the new crop generated the new pore structure. This possibly caused the inconsistent impact of manure on gas transport among the different crop types.

Compared to the grass plots, the maize plots exhibited opposite features, namely, high aeration, low PAW and highly developed structure, especially for the manure treatments. As a row crop, the density of crop in the plot is much lower than the grass, wheat and barley. Moreover, root growth is often associated with soil fragmentation where roots loosen the soil during root elongation (Angers and Caron, 1998). The maize root cortex is around three times thicker and the cross-section area is larger than those of wheat and barley (Lipiec et al., 2012). The thicker roots may facilitate the improvement of soil aeration and pore connectivity, causing higher D_p/D_0, k_a and K_{sat} (Fig. 4e; Fig. 5e; Table 2).

Tillage may also play an important role in the impact on soil pore structure. The soil in the grass plots had settled for 18 months before sampling whereas, for maize, it was around 5 months. Therefore, grass/clover plots were more compacted than the maize plots. Furthermore, the longer post-ploughing soil settling time for the winter-sown crop (wheat) may have resulted in higher WSA than for the spring-sown crops (maize and barley) (Fig. 6c). On the contrary, the maize in the silty site showed different results, although maize in both sites had lower WSA (Fig. 6). The poor pore structure of the silty maize plots may be due to the drought and the high ρ_b and low ϕ limited root growth (Haling et al., 2014). The higher ρ_b in the silty site may have caused the change in maize root shape and the response of root anatomy to compaction was greater for maize than for barley and wheat (Lipiec et al., 2012).

Furthermore, barley has longer root hairs that bound to soil particles and facilitate the creation of aggregates than maize (Burak et al., 2021). The longer root hairs, together with the higher barley crop density in the field than maize may be the reasons why the barley plots had better soil pore structure than the maize plots in the silty site. Shakoor et al. (2021) found the highest CO_2 emission was associated with barley fields than wheat and maize. In the sandy site, although barley and wheat are functionally similar, they exhibited slightly different trends and it may be attributed to the sowing time. The winter wheat was sown in winter and the barley was sown in spring. The time for roots interacting with soil was different for these two crops. Moreover, the duration between ploughing and sampling was different for barley and wheat, because of the intrinsic difference in the management of winter crops and summer crops. Therefore, in the sandy site Askov, the pore structure of wheat was different from barley, with a more homogeneous pore structure in the former plots and more heterogeneous pores in the latter plots (Fig. 5d & f). The undersown grass in the barley plots may also have altered the soil pore structure.

5. Conclusion

This study investigated the effect of manure on soil chemical, hydraulic and structural properties of soils with three contrasting textures under different crop types. The results proved that long-term manure application can increase SOC and nutrient level, reduce soil ρ_b and improve soil water retention, plant available water and water-stable aggregates for most plots investigated, regardless of soil texture. Contrary to our hypothesis, the effect of manure was more pronounced on the silty site rather than on the sandy site. The rate of manure applied had little difference in soil water retention and structural properties. The effect of manure on soil gas transport, pore network and K_{sat} varied with soil type and crop type. In the clayey soil, manure increased gas diffusion and K_{sat} while BF had the highest K_{sat} and k_a. In the silty soil, manure decreased gas transport and K_{sat} in the barley plots, while in the maize plots, the soil pore structure was poorly developed, and the manure seemed to make no difference in K_{sat} and a little in gas transport (mainly at low water potentials). In these two fine-textured sites, manure increases the microporosity and the anaerobic microbial activity is more likely prevalent at the field capacity. In the sandy site, manure increased gas transport on all plots except for the barley plots. The soil pore structure of the maize plots was more developed with high gas transport and K_{sat}. The management for each crop type, i.e. the duration between tillage and sampling, may have had an impact on the results, alongside the intrinsic difference in plant root systems.

In perspective, the lack of a significant improvement in soil properties in tandem with increasing manure rates suggest that in long-term cultivated fields, increasing the rates of manure between 20 and 37.5 t ha^{-1} may not lead to significant improvements in soil physical properties. Moreover, the crop rotation sequence may be less important than the crop type in an intensively cultivated field and including 1.5 yrs grass/clover in the rotation can temporarily improve soil physical and chemical properties.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Angers, D.A., Caron, J., 1998. Plant-induced changes in soil structure: Processes and feedbacks. Biogeochemistry 42, 55–72.

Angers, D.A., Bullock, M.S., Mehuys, G.R., 2007. Chapter 62. Aggregate stability to water, in: Carter, M.., Gregorich, E, G. (Eds.), Soil Sampling and Methods of Analysis, Second Edition. pp. 811–818.

Aoyama, M., Angers, D.A., N'Dayegamiye, A., 1999. Particulate and mineral-associated organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. Can. J. Soil Sci. 79, 295–302.

Arthur, E., Moldrup, P., Schjønning, P., Jonge, L.W., 2012. Linking Particle and Pore Size Distribution Parameters to Soil Gas Transport Properties. Soil Sci. Soc. Am. J. 76, 18–27.

Arthur, E., Moldrup, P., Schjønning, P., de Jonge, L.W., 2013. Water Retention, Gas Transport, and Pore Network Complexity during Short-Term Regeneration of Soil Structure. Soil Sci. Soc. Am. J. 77, 1965–1976.

Azeez, J.O., van Averbeke, W., 2012. Dynamics of Soil pH and Electrical Conductivity with the Application of Three Animal Manures. Commun. Soil Sci. Plant Anal. 43, 865–874.

Bacq-Labreuil, A., Neal, A.L., Crawford, J., Mooney, S.J., Akkari, E., Zhang, X., Clark, I., Ritz, K., 2021. Significant structural evolution of a long-term fallow soil in response to agricultural management practices requires at least 10 years after conversion. Eur. J. Soil Sci. 72, 829–841.

Bai, Z., Caspari, T., Gonzalez, M.R., Batjes, N.H., Mäder, P., Bünemann, E.K., de Goede, R., Brussaard, L., Xu, M., Ferreira, C.S.S., Reintam, E., Fan, H., Mihelič, R., Glavan, M., Tóth, Z., 2018. Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. Agric. Ecosyst. Environ. 265, 1–7.

Ball, B.C., Bingham, I., Rees, R.M., Watson, C.A., Litterick, A., 2005. The role of crop rotations in determining soil structure and crop growth conditions. Can. J. Soil Sci. 85, 557–577.

Barré, P., Eglin, T., Christensen, B.T., Ciais, P., Houot, S., Kätterer, T., Van Oort, F., Peylin, P., Poulton, P.R., Romanenkov, V., Chenu, C., 2010. Quantifying and isolating stable soil organic carbon using long-term bare fallow experiments. Biogeosciences 7, 3839–3850.

Bhattacharyya, R., Chandra, S., Singh, R.D., Kundu, S., Srivastva, A.K., Gupta, H.S., 2007. Long-term farmyard manure application effects on properties of a silty clay loam soil under irrigated wheat-soybean rotation. Soil Tillage Res. 94, 386–396.

Blanco-Canqui, H., Benjamin, J.G., 2013. Impacts of soil organic carbon on soil physical behavior, in: Logsdon, S., Berli, M., Horn, R. (Eds.), Quantifying and Modeling Soil Structure Dynamics. Advances in Agricultural Systems Modeling. pp. 11–40.

Blanco-Canqui, H., Hergert, G.W., Nielsen, R.A., 2015. Cattle Manure Application Reduces Soil Compactibility and Increases Water Retention after 71 Years. Soil Sci. Soc. Am. J. 79, 212–223.

Bolluyt, J., Johnson, S.E., Lowy, P., McGrath, M.T., Mohler, C.L., Rangarajan, A., Stoner, K.A., Toensmeier, E., van Es, H., 2009. Crop Rotation on Organic Farms A Planning Manual (NRAES-177).

Bullock, D.G., 1992. Crop rotation. CRC. Crit. Rev. Plant Sci. 11, 309–326.

Burak, E., Quinton, J.N., Dodd, I.C., 2021. Root hairs are the most important root trait for rhizosheath formation of barley (Hordeum vulgare), maize (Zea mays) and Lotus japonicus (Gifu). Ann. Bot. 128, 45–57.

Candemir, F., Gülser, C., 2012. Influencing Factors and Prediction of Hydraulic Conductivity in Fine-Textured Alkaline Soils. Arid L. Res. Manage. 26, 15–31.

Christensen, B.T., Thomsen, I.K., Eriksen, J., 2019. The Askov long-term experiments: 1894-2019 - a unique research platform turns 125 years. DCA report No. 151.

de Jonge, L.W., Moldrup, P., Schjonning, P., 2009. Soil infrastructure, interfaces & translocation processes in inner space ("Soil-it-is"): Towards a road map for the constraints and crossroads of soil architecture and biophysical processes. Hydrol. Earth Syst. Sci. 13, 1485–1502.

Deepagoda, T.K.K.C., Moldrup, P., Schjønning, P., de Jonge, L.W., Kawamoto, K., Komatsu, T., 2011. Density-Corrected Models for Gas Diffusivity and Air Permeability in Unsaturated Soil. Vadose Zo. J. 10, 226–238.

Eden, M., Moldrup, P., Schjønning, P., Vogel, H.J., Scow, K.M., De Jonge, L.W., 2012. Linking soil physical parameters along a density gradient in a loess-soil long-term experiment. Soil Sci. 177, 1–11.

Fang, H., Liu, K., Li, D., Peng, X., Zhang, W., Zhou, H., 2021. Long-term effects of inorganic fertilizers and organic manures on the structure of a paddy soil. Soil Tillage Res. 213, 105137.

Fujikawa, T., Miyazaki, T., 2005. Effects of bulk density and soil type on the gas diffusion coefficient in repacked and undisturbed soils. Soil Sci. 170, 892–901.

Garcia, R.A., Li, Y., Rosolem, C.A., 2013. Soil Organic Matter and Physical Attributes Affected by Crop Rotation Under No-till. Soil Sci. Soc. Am. J. 77, 1724–1731.

Gee, G.W., Or, D., 2002. 2.4 Particle-Size Analysis, in: Methods of Soil Analysis Part 4 Physical Methods SSSA Book Series. pp. 255–293.

Haling, R.E., Brown, L.K., Bengough, A.G., Valentine, T.A., White, P.J., Young, I.M., George, T.S., 2014. Root hair length and rhizosheath mass depend on soil porosity, strength and water content in barley genotypes. Planta 239, 643–651.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter. Nutr. Cycl. Agroecosystems 51, 123–137.

Hu, T., Chabbi, A., 2022. Grassland management and integration during crop rotation impact soil carbon changes and grass-crop production. Agric. Ecosyst. Environ. 324, 107703.

Jensen, J.L., Schjønning, P., Christensen, B.T., Munkholm, L.J., 2017. Suboptimal fertilisation compromises soil physical properties of a hard-setting sandy loam. Soil Res. 55, 332–340.

Jensen, J.L., Schjønning, P., Watts, C.W., Christensen, B.T., Peltre, C., Munkholm, L.J., 2019. Relating soil C and organic matter fractions to soil structural stability. Geoderma 337, 834–843.

Jensen, J.L., Beucher, A.M., Eriksen, J., 2022. Soil Organic C and N Stock Changes in Grass-Clover Leys: Effect of Grassland Proportion and Organic Fertilizer. SSRN Electron. J. 1–25.

Kätterer, T., Börjesson, G., Kirchmann, H., 2014. Changes in organic carbon in topsoil and subsoil and microbial community composition caused by repeated additions of organic amendments and N fertilisation in a long-term field experiment in Sweden. Agric. Ecosyst. Environ. 189, 110–118.

Kawamoto, K., Moldrup, P., Schjønning, P., Iversen, B.V., Komatsu, T., Rolston, D.E., 2006. Gas Transport Parameters in the Vadose Zone: Development and Tests of Power-Law Models for Air Permeability. Vadose Zo. J. 5, 1205–1215.

Keiluweit, M., Wanzek, T., Kleber, M., Nico, P., Fendorf, S., 2017. Anaerobic microsites have an unaccounted role in soil carbon stabilization. Nat. Commun. 8, 1–8.

Keller, T., Sutter, J.A., Nissen, K., Rydberg, T., 2012. Using field measurement of saturated soil hydraulic conductivity to detect low-yielding zones in three Swedish fields. Soil Tillage Res. 124, 68–77.

Klute, A., Dirksen, C., 1986. Hydraulic Conductivity and Diffusivity: Laboratory Methods, in: Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods Second Edition. pp. 694–700.

Körschens, M., Albert, E., Armbruster, M., Barkusky, D., Baumecker, M., Behle-Schalk, L., Bischoff, R., Čergan, Z., Ellmer, F., Herbst, F., Hoffmann, S., Hofmann, B., Kismanyoky, T., Kubat, J., Kunzova, E., Lopez-Fando, C., Merbach, I., Merbach, W., Pardor, M.T., Rogasik, J., Rühlmann, J., Spiegel, H., Schulz, E., Tajnsek, A., Toth, Z., Wegener, H., Zorn, W., 2013. Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. Arch. Agron. Soil Sci. 59, 1017–1040.

Kravchenko, A.N., Guber, A.K., 2017. Soil pores and their contributions to soil carbon processes. Geoderma 287, 31–39.

Kreba, S.A., Wendroth, O., Coyne, M.S., Walton, R., 2017. Soil Gas Diffusivity, Air-Filled Porosity, and Pore Continuity: Land Use and Spatial Patterns. Soil Sci. Soc. Am. J. 81, 477–489.

Lal, R., 2020. Soil organic matter and water retention. Agron. J. 112, 3265–3277.

Liang, Q., Chen, H., Gong, Y., Fan, M., Yang, H., Lal, R., Kuzyakov, Y., 2012. Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a wheat-maize system in the North China Plain. Nutr. Cycl. Agroecosystems 92, 21–33.

Lin, Y., Ye, G., Kuzyakov, Y., Liu, D., Fan, J., Ding, W., 2019. Long-term manure application increases soil organic matter and aggregation, and alters microbial community structure and keystone taxa. Soil Biol. Biochem. 134, 187–196.

Lipiec, J., Horn, R., Pietrusiewicz, J., Siczek, A., 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil Tillage Res. 121, 74–81.

Marshall, T.J., 1959. The diffusion of gases through porous media. J. Soil Sci. 10, 79–82.

Materechera, S.A., Kirby, J.M., Alston, A.M., Dexter, A.R., 1994. Modification of soil aggregation by watering regime and roots growing through beds of large aggregates. Plant Soil 160, 57–66.

Merbach, I., Schulz, E., 2013. Long-term fertilization effects on crop yields, soil fertility and sustainability in the Static Fertilization Experiment Bad Lauchstädt under climatic conditions 2001–2010. Arch. Agron. Soil Sci. 59, 1041–1057.

Miller, J.J., Sweetland, N.J., Chang, C., 2002. Hydrological Properties of a Clay Loam Soil after Long-Term Cattle Manure Application. J. Environ. Qual. 31, 989–996.

Moldrup, P., Olesen, T., Schjønning, P., Yamaguchi, T., Rolston, D.E., 2000. Predicting the Gas Diffusion Coefficient in Undisturbed Soil from Soil Water Characteristics. Soil Sci. Soc. Am. J. 64, 94–100.

Moldrup, P., Olesen, T., Komatsu, T., Schjønning, P., Rolston, D.E., 2001. Tortuosity, Diffusivity, and Permeability in the Soil Liquid and Gaseous Phases. Soil Sci. Soc. Am. J. 65, 613–623.

Naveed, M., Moldrup, P., Vogel, H.J., Lamandé, M., Wildenschild, D., Tuller, M., de Jonge, L.W., 2014. Impact of long-term fertilization practice on soil structure evolution. Geoderma 217–218, 181–189.

Ozlu, E., Kumar, S., 2018. Response of Soil Organic Carbon, pH, Electrical Conductivity, and Water Stable Aggregates to Long-Term Annual Manure and Inorganic Fertilizer. Soil Sci. Soc. Am. J. 82, 1243–1251.

Patil, I., 2019. pairwiseComparisons: Multiple Pairwise Comparison Tests.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rasmussen, P.E., Goulding, K.W.T., Brown, J.R., Grace, P.R., Janzen, H.H., Korschens, M., 1998. Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. Science (80-.). 282, 893–896.

Riley, H., Pommeresche, R., Eltun, R., Hansen, S., Korsaeth, A., 2008. Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. Agric. Ecosyst. Environ. 124, 275–284.

Schjønning, P., Munkholm, L.J., Moldrup, P., Jacobsen, O.H., 2002. Modelling soil pore characteristics from measurements of air exchange: The long-term effects of fertilization and crop rotation. Eur. J. Soil Sci. 53, 331–339.

Schjønning, P., Thomsen, I.K., Moldrup, P., Christensen, B.T., 2003. Linking Soil Microbial Activity to Water- and Air-Phase Contents and Diffusivities. Soil Sci. Soc. Am. J. 67, 156–165.

Schjønning, P., Iversen, B.V., Munkholm, L.J., Labouriau, R., Jacobsen, O.H., 2005. Pore characteristics and hydraulic properties of a sandy loam supplied for a century with either animal manure or mineral fertilizers. Soil Use Manag. 21, 265–275.

Schjønning, P., Koppelgaard, M., 2017. The Forchheimer Approach for Soil Air Permeability Measurement. Soil Sci. Soc. Am. J. 81, 1045–1053.

Schjønning, P., Eden, M., Moldrup, P., de Jonge, L.W., 2013. Two-Chamber, Two-Gas and One-Chamber, One-Gas Methods for Measuring the Soil-Gas Diffusion Coefficient: Validation and Inter-calibration. Soil Sci. Soc. Am. J. 77, 729–740.
Schjønning, P., McBride, R.A., Keller, T., Obour, P.B., 2017. Predicting soil particle density from clay and soil organic matter contents. Geoderma 286, 83–87.
Shakoor, A., Shakoor, S., Rehman, A., Ashraf, F., Abdullah, M., Shahzad, S.M., Farooq, T. H., Ashraf, M., Manzoor, M.A., Altaf, M.M., Altaf, M.A., 2021. Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils—A global meta-analysis. J. Clean. Prod. 278, 124019.
Sissingh, H.A., 1971. Analytical technique of the Pw method, used for the assessment of the phosphate status of arable soils in the Netherlands. Plant Soil 34, 483–486.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241, 155–176.
Soil Survey Staff - NRCS/USDA, 2014. Keys to soil taxonomy, United States Department of Agriculture. Washington, D.C.
Soil Science Division Staff (USDA-NRCS), 2017. Soil Survey Manual, USDA Handbook 18, Gov. Printing Office.
Stirzaker, R.J., Passioura, J.B., Wilms, Y., 1996. Soil structure and plant growth: Impact of bulk density and biopores. Plant Soil 185, 151–162.
Taylor, S.A., 1950. Oxygen Diffusion in Porous Media as a Measure of Soil Aeration. Soil Sci. Soc. Am. J. 14, 55–61.
Tecon, R., Or, D., 2017. Biophysical processes supporting the diversity of microbial life in soil. FEMS Microbiol. Rev. 41, 599–623.
Whalen, J.K., Chang, C., Clayton, G.W., Carefoot, J.P., 2000. Cattle Manure Amendments Can Increase the pH of Acid Soils. Soil Sci. Soc. Am. J. 64, 962–966.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.
Yang, X., Ren, W., Sun, B., Zhang, S., 2012. Effects of contrasting soil management regimes on total and labile soil organic carbon fractions in a loess soil in China. Geoderma 177–178, 49–56.
Yläranta, T., Uusi-Kämppä, J., Jaakkola, A., 1996. Leaching of phosphorus, calcium, magnesium and potassium in barley, grass and fallow lysimeters. Acta Agric. Scand. Sect. B Soil Plant Sci. 46, 9–17.
Zaffar, M., Lu, S.G., 2015. Pore size distribution of clayey soils and its correlation with soil organic matter. Pedosphere 25, 240–249.
Zhang, X., Neal, A.L., Crawford, J.W., Bacq-Labreuil, A., Akkari, E., Rickard, W., 2021. The effects of long-term fertilizations on soil hydraulic properties vary with scales. J. Hydrol. 593, 125890.