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Research Article

Effect of organic residues on soil properties of loamy topsoil of haplic Luvisol in Northern Germany

Einfluss organischer Rückstände auf die Bodeneigenschaften eines lehmigen Oberbodens einer Parabraunerde in Norddeutschland

Steffen Beck-Broichsitter[1]*, Heiner Fleige[2], Rainer Horn[2]

[1] Research Area 1 "Landscape Functioning, Working Group “Hydropedologie”, Leibniz Centre of Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany
2 Institute of Plant Nutrition and Soil Science, Christian Albrechts University Kiel, Hermann-Rodewald-Straße 2, 24118 Kiel, Germany

* Corresponding author: steffen.beck-broichsitter@zalf.de

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Summary

The application of organic residues should ensure a sufficient air capacity (AC) and plant available water capacity (AWC) to improve the soil aeration and water supply for plant roots, whereas the air permeability (k_a) primarily depends on the number of functional and, therefore, connected pores. The objective of the study was to investigate the effect of digestates derived from maize (*Zea mays* L.), sugar beet (*Beta vulgaris* L.), and wheat (*Triticum aestivum* L.) in ratios of 100%, 80%, and 20%, respectively; compost of shrub debris; and sewage sludge on AC, AWC, and ka values, including the pore continuity indices (c_2, c_3) of a loamy Ap horizon of a haplic Luvisol. The results indicate that AC values increase from 0.142 of up to 0.191 $cm^3\ cm^{-3}$, but pore continuities and AWC values decrease from 0.143 down to 0.111 $cm^3\ cm^{-3}$, except for wheat-containing digestate (20w80b), which shows an opposite trend. The application of organic residues can compensate low AC values but not the AWC values. The wheat-containing digestate should be preferred for improving the water-holding capacity and, therefore, the water supply for plant roots.

Keywords: organic residues, air capacity, water holding capacity, air permeability

Zusammenfassung

Die Ausbringung von organischen Rückständen soll eine ausreichende Luftkapazität und nutzbare Feldkapazität gewährleisten, um die Bodenbelüftung und das Wasserdargebot für die Pflanzenwurzeln zu verbessern, wobei die Luftpermeabilität, k_a ebenso wie die in diesem Beitrag nicht behandelte Wasserleitfähigkeit vorrangig durch die Anzahl an funktionalen und verbundenen Poren bestimmt werden. Das Ziel der Studie war die Untersuchung des Einflusses von Gärresten aus Mais (*Zea mays* L.), Zuckerrübe (*Beta vulgaris* L.) und Weizen (*Triticum aestivum* L.) in Anteilen von 100 %, 80 % und 20 %, Kompost aus Strauchresten und Klärschlamm auf die Luftkapazität, nutzbare Feldkapazität und Luftpermeabilität sowie den Porenkontinuitätsindizes (c2, c3) eines lehmigen Ap-Horizonts einer Parabraunerde. Die Ergebnisse zeigen steigende Luftkapazitäten von 0,142 auf 0,191 $cm^3\ cm^{-3}$, jedoch abnehmende Porenkontinuitäten und nutzbare Feldkapazitäten von 0,143 auf 0,111 $cm^3\ cm^{-3}$, mit Ausnahme des weizenhaltigen Gärrests (20w80b), der einen entgegengesetzten Trend zeigt. Die Ausbringung organischer Rückstände kann geringe Luftkapazitäten kompensieren, jedoch nicht die nutzbare Feldkapazität. Der weizenhaltige Gärrest sollte bevorzugt eingesetzt werden, um die Wasserspeicherkapazität und dementsprechend das Wasserdargebot für die Pflanzenwurzeln zu verbessern.

Schlagworte: Organische Rückstände, Luftkapazität, Wasserspeicherkapazität, Luftpermeabilität

1. Introduction

In terms of a sustainable energy and waste management, by products in form of aerobically composted or anaerobically digested organic materials can be used as cost-effective organic fertilizer in agriculture (Risberg et al., 2017). These organic residues can also be used as soil structure conditioner (Beck-Broichsitter et al., 2018) to improve the nutrient and water supply for plants (Duong et al., 2012), soil aeration (Reszkowska et al., 2011), and root growth (Möller and Müller, 2012). The impact of organic residues on soil chemical properties, for example, organic carbon (OC) and nutrient supply (Voelkner et al., 2015a) or wettability (Beck-Broichsitter et al., 2020b) is comprehensively analyzed, whereas a lack of information is still existing for physical properties including the plant available water capacity and air permeability.

The process of soil aeration is important for the root growth and the crop production of arable soils (Zhai and Horn, 2018; Beck-Broichsitter et al., 2020a). This includes a sufficient continuity of pores and a stable pore network (Horn et al., 2014), but tilled topsoils are known for discontinuities in the pore system through mechanically induced homogenization compared to non-tilled topsoils (Lipiec et al., 2003; Dörner et al., 2012; Assis et al., 2016). The effect of application of organic residues on the pore continuity can be evaluated using the c_2 and c_3 indices that consider the relation between air permeability, k_a, and air-filled porosity, ε_a, of soils (Groenevelt et al., 1984; Ivelic-Sáez et al., 2015).

The objective of the study is to determine the effect of application of compost, sewage sludge, and digestates containing maize, sugar beet, and winter wheat on nutrient availability, capacity parameters (air capacity [AC] and plant AWC), and intensity parameters (air permeability) of a glacial till-derived Ap horizon of a haplic Luvisol under agricultural use.

The authors hypothesize that the application of organic residues will increase the AC and plant AWC and decrease the pore continuity (c_2 and c_3 indices) of the untreated loam.

2. Materials and methods

2.1. Basic characteristics of soil material and organic residues

For the laboratory research, disturbed soil material was sampled from the Ap horizon (0–0.3 m in depth) of an agricultural-used and glacial till-derived haplic Luvisol (horizon sequence: Ap/E/Bt/Bw/C) (IUSS Working Group WRB, 2014), located at the research farm in Hohenschulen (54°31'28"N, 9°98'35"E) in Northern Germany. The silage from maize, sugar beet, and winter wheat were derived from the biogas plant in Schleswig-Holstein. The liquid digestates (i) 80% maize and 20% sugar beet (80m20b), (ii) 20% maize and 80% sugar beet (20m80b), and (iii) 20% winter wheat and 80% sugar beet (20w80b) were generated in a batch fermentation process. The compost (com) was produced by the local composting facility in Schleswig-Holstein, made out of shrub chippings (Beck-Broichsitter et al., 2018), whereas the sewage sludge (sl) and the associated chemical properties were derived from the municipal wastewater treatment plant in Schleswig-Holstein.

The texture of the soil material was classified as loam (FAO, 2006) consisting of 550 g kg^{-1} sand, 300 g kg^{-1} silt, and 150 g kg^{-1} clay with an OC content of 11.96 g kg^{-1}, and pH of 6.79. The organic residues indicate pH values between 7.47 and 8.08 and, for example, total nitrogen contents between 1.2 and 4.0 kg m^{-3} organic mass^{-1} (Table 1).

2.2. Sample preparation and laboratory analysis

The organic residues were air dried, sieved (≤2 mm), and mechanically mixed with the loam (θ of approximately 0.1 cm^3 cm^{-3}) to simulate the annual application rates for fertilizer in 0.3-m Ap horizon with 30 Mg dry mass ha^{-1} for compost and 30 m^3 moist mass ha^{-1} for digestates and sewage sludge. After the application of the organic residues, particle density (ρ_s; g cm^{-3}), using pycnometer method; OC (g kg^{-1}), using coulometric carbon dioxide (CO_2) measurement; potential cation exchange capacity, CEC_{pot} (cmolc kg^{-1}), including natrium (Na), potassium (K), magnesium (Mg), and calcium (Ca), using barium chloride method; texture, using combined sieve and pipette method; soil pH values (in 0.01M $CaCl_2$ solution); and saturated hydraulic conductivity, Ks (cm d^{-1}), using by steady-state flow method were analysed following Hartge and Horn (2016).

Furthermore, the loam and the residue mixtures were compacted to a dry bulk density, ρ_b (g cm^{-3}) of approximately 1.45 g cm^{-3} by a load frame (Instron 8871, Norwood, USA) with a pressing force of 5 kN, resulting in 8–10 soil cores (diameter: 5.5 cm; height: 4 cm) each.

2.3. Soil water retention characteristics

The volumetric water content (θ_v) for the different drying stages was from the soil cores with 8–10 replicates per depth by a combined pressure plate (saturated, –60 hPa, and –300 hPa) and ceramic vacuum outflow method (–15,000 hPa) as well as oven dried for 24 hours at 105°C. The air-filled porosity (ε_a) was calculated as follows:

$$\varepsilon_a = \left[\left(1 - \frac{\rho_b}{\rho_s}\right) - \theta_v\right] \tag{1}$$

where ρ_b is the dry bulk density (g cm^{-3}), ρ_s is the particle density (g cm^{-3}), here a value of 2.65 g cm^{-3} for ρ_s was assumed for the quartz-dominated soil, and θ_v is the volumetric water content (cm^3 cm^{-3}).

The soil porosity, ε, was calculated as:

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} \tag{2}$$

The AC (cm^3 cm^{-3}) and the plant AWC (cm^3 cm^{-3}) were calculated using the following equations:

$$AC = \varepsilon - \theta_{-60\,hPa} \tag{3}$$

$$AWC = \theta_{-60\,hPa} - \theta_{-15000\,hPa} \tag{4}$$

where $\theta_{-60\,hPa}$ and $\theta_{-15000\,hPa}$ correspond to the water content at pressure heads, h, of –60 and –15,000 hPa, respectively. The German soil classification system (Ad-hoc-AG-Boden, 2005) was used to classify the AC and AWC values.

2.4. Air permeability and pore continuity indices

The air conductivity (k_l) was simultaneously determined from the same samples (100 cm^3) as used for measuring soil water retention characteristics at –60, –300, and –15,000 hPa and in dry stage (105°C, 24 h) using an air flow meter with different scales between 0.1 and 10 L m^{-1} (Key Instruments, Trevor, USA) (for more details, see Zhai and Horn, 2018):

$$k_l = \rho_l \cdot g \cdot \frac{\Delta V \cdot \Delta l}{\Delta t \cdot \Delta p \cdot \Delta A} \tag{5}$$

where ρ_l is the air density (kg m^{-3}), $\Delta\rho$ is the flow pressure (hPa), ΔV is the volume of air flow (m^3) through the soil sample during time Δt (min), and g is the acceleration of gravity (m s^{-1}). The air density (ρ_l) was determined to calculate the kl values, whereas the atmospheric pressure and the temperature were obtained simultaneously (Dörner and Horn, 2006):

$$\rho_l = \rho_n * \frac{273.15 * \rho_L}{1013 * (273.15 + T)} \tag{6}$$

where ρ_l is the air density (kg m^{-3}), ρ_n is density of the air (1.293 kg m^{-3}), ρ_L is air pressure (mbar), and T is laboratory temperature (°C) for each measurement time.

Table 1. Basic characteristics of loam and organic residues: (i) 80% maize and 20% sugar beet (80m20b), (ii) 20% maize and 80% sugar beet (20m80b), and (iii) 20% winter wheat and 80% sugar beet (20w80b); compost (com); and sewage sludge (sl) with two repeated measurements each and symbol ± corresponds to the standard deviation.

Tabelle 1. Grundlegende Eigenschaften des Lehms und der organischen Rückstände: (i) 80 % Mais und 20 % Zuckerrübe (80m20b), (ii) 20 % Mais und 80 % Zuckerrübe (20m80b) und (iii) 20 % Weizen und 80 % Zuckerrübe (20w80b), Kompost (com) und Klärschlamm (sl) mit jeweils zwei Messwiederholungen und das Symbol ± entspricht der Standardabweichung.

Parameters	**Loam**	**com**	**sl**	**80m20b**	**20m80b**	**20w80b**
pH_{CaCl2} (–)	6.79 ± 0.3	8.08 ± 0.6	7.47 ± 0.3	7.74 ± 0.3	7.72 ± 0.3	7.78 ± 0.4
OC (g kg^{-1})	11.96 ± 2.3	-	-	-	-	-
dm (%)	-	52.0 ± 4	-	5.51 ± 0.2	5.38 ± 0.3	5.38 ± 0.1
NH4-N (kg m^3 om^{-1})	-	-	-	1.95 ± 0.3	2.09 ± 0.3	2.08 ± 0.4
Ntotal (kg m^3 om^{-1})	-	1.24 ± 0.2	4.02 ± 0.3*	2.82 ± 0.1	2.87 ± 0.2	2.32 ± 0.1
P (g kg dm^{-1})	-	1.97 ± 0.2	2.46 ± 0.2*	23.5 ± 1.1	23.6 ± 1.8	27.3 ± 1.9
K (g kg dm^{-1})	-	5.95 ± 0.5	3.49 ± 0.3*	71.9 ± 3.4	75.1 ± 2.9	74.4 ± 3.1
Mg (g kg dm^{-1})	-	4.03 ± 0.4	1.96 ± 0.1*	10.1 ± 0.9	10.4 ± 1.1	13.0 ± 0.8
Ca (g kg dm^{-1})	-	21.9 ± 1.6	-	28.3 ± 1.4	28.7 ± 2.1	31.5 ± 1.8
Na (g kg dm^{-1})	-	-	-	3.24 ± 0.2	3.03 ± 0.1	3.59 ± 0.1
C/N (–)	10 ± 0.9	-	-	8.02 ± 0.3	7.97 ± 0.2	9.98 ± 0.2

dm = dry mass; om = organic mass; C/N = carbon-to-nitrogen ratio; * g kg moist mass.

In addition, the air permeability, k_a, was calculated based on the air conductivity, k_l (cm s^{-1}), considering Darcy's law with the following formula (Ball et al., 1981; Dörner and Horn, 2006):

$$k_a = \frac{k_l \cdot \eta}{\rho_l \cdot g} \qquad 7$$

where η is the air viscosity (g s^{-1} cm^{-1}).

The pore continuity was determined using the c_2 and c_3 indices as proposed by Groenevelt et al. (1984) and Zhai and Horn (2018). The indices are calculated as relationship between k_a and ε_a and also $\varepsilon_a{}^2$ in the following form (Ball et al., 1988; Dörner and Horn, 2006):

$$c_2 = \frac{k_a}{\varepsilon_a} \qquad 8$$

$$c_3 = \frac{k_a}{\varepsilon_a^2} \qquad 9$$

Furthermore, soils with similar pore size distribution and porosity continuity have analog c_2 values, whereas soils with similar c_3 values only have analog pore size distribution (Groenevelt et al., 1984). In additionally, differences between c_2 and c_3 are related to differences in the pore continuity, independent from the pore size distribution (Dörner and Horn, 2006).

The following exponential relation between k_a and ε_a was suggested by Ball et al. (1988):

$$\log(k_a) = \log(M) \cdot N\log(\varepsilon_a) \qquad 10$$

where M is an empirical parameter. N is the pore continuity index, which reflects the increase in k_a with increasing ε_a or the decrease in the pore tortuosity and surface area with increasing fraction of pores available to flow (Ball et al., 1988). In addition, the blocked air-filled pore space (ε_b, cm^3 cm^{-3}), is defined as follows:

$$\varepsilon_b = 10^{\frac{(-\log M)}{N}} \qquad 11$$

2.5. Statistical analysis

The statistical software R (R Development Core Team, 2014) was used to evaluate the data. The data were tested for normal distribution and heteroscedasticity on the Shapiro–Wilk test and graphical residue analysis. An analysis of variance (ANOVA) was conducted with $p<0.05$ followed by Tukey's HSD (honestly significant difference) test (*$p\leq0.05$, **$p\leq0.01$, ***$p\leq0.001$, and ****$p\leq0.0001$) following Hasler and Horton (2008) to evaluate the differences between loam and the loam residue mixture in basic soil characteristics (see Table 2), AC, plant AWC (see Table 3), and their interaction terms (twofold and

Table 2. Soil characteristics after the application of the organic residues to loam: (i) 80% maize and 20% sugar beet (80m20b), (ii) 20% maize and 80% sugar beet (20m80b), and (ii) 20% winter wheat and 80% sugar beet (20w80b); compost (com); and sewage sludge (sl) for two repeated measurements each, and symbol ± corresponds to the standard deviation. Differences in mean values compared to loam were significant at p<0.05 (*), p<0.01 (**), p<0.001 (***), and p<0.0001 (****) for ANOVA.

Tabelle 2. Bodeneigenschaften nach der Zuführung der organischen Rückstände zum Lehm: (i) 80 % Mais und 20 % Zuckerrübe (80m20b), (ii) 20 % Mais und 80 % Zuckerrübe (20m80b) und (iii) 20 % Weizen und 80 % Zuckerrübe (20w80b), Kompost (com) und Klärschlamm (sl) mit jeweils zwei Messwiederholungen und das Symbol ± entspricht der Standardabweichung. Abweichungen zum Mittelwert des Lehms sind bei der ANOVA signifikant bei p<0,05 (*), <0,01 (**), <0,001 (***), <0,0001 (****).

Parameters	**Loam**	**com**	**sl**	**80m20b**	**20m80b**	**20w80b**
pH_{CaCl2} (–)	6.79 ± 0.3	6.87 ± 0.3	6.75 ± 0.3	6.62 ± 0.4	6.59 ± 0.6	6.65 ± 0.3
CEC_{pot} (cmolc kg^{-1})	9.39 ± 1.4	11.1 ± 1.5*	9.78 ± 0.7	10.2 ± 0.8	9.58 ± 0.6	9.68 ± 0.6
Na (cmolc kg^{-1})	0.11 ± 0.1	0.12 ± 0.1	0.11 ± 0.1	0.25 ± 0.1****	0.12 ± 0.1	0.12 ± 0.1
K (cmolc kg^{-1})	0.64 ± 0.1	0.83 ± 0.1**	0.68 ± 0.1	1.23 ± 0.1****	1.24 ± 0.2****	1.19 ± 0.2****
Mg (cmolc kg^{-1})	2.35 ± 0.1	2.38 ± 0.3	2.39 ± 0.2	2.58 ± 0.3	2.61 ± 0.2	2.51 ± 0.3
Ca (cmolc kg^{-1})	7.71 ± 0.9	8.56 ± 0.7	8.21 ± 1.1	8.24 ± 0.9	8.31 ± 0.8	7.97 ± 0.9
OC (g kg^{-1})	12.4 ± 1.4	13.5 ± 1.9	12.2 ± 1.1	14.1 ± 1.7	14.3 ± 1.5*	13.2 ± 1.2
N_{total} (g kg^{-1})	1.19 ± 0.1	1.28 ± 0.1	1.31 ± 0.1	1.52 ± 0.2	1.61 ± 0.1	1.48 ± 0.1
C/N ratio	10 ± 0.4	10 ± 0.6	10 ± 0.6	9 ± 0.3	9 ± 0.4	9 ± 0.3

dm = dry mass; om = organic mass; C/N = organic carbon (OC)-to-total nitrogen (N_{total}) ratio; n.a. = not analyzed; * g kg moist mass.

threefold), respectively. The coefficient of determination (r^2) is an index for the goodness of fit.

3. Results

3.1. Basic soil characteristics after application of organic residues

The results show that the OC content of the loam was improved through application of organic residue (12.4 up to 14.3 g kg^{-1}). There are very small differences in weak acidic pH values between 6.59 and 6.87, whereas application of compost (com) increases and application of digestate decreases the pH value (Table 2). The calcium (Ca) and especially the potassium (K) content significantly increased through application of organic residue from 0.64 up to 1.24 cmolc kg^{-1}. The C/N ratios between 9 and 10 indicate easily decomposable organic substances and, therefore, a rapid available nutrient source for plants.

3.2. Soil water retention characteristics and air permeability after application of organic residues

The results indicate medium to high total porosities and the application of organic residues slightly decreased the porosity values, except for 20m80b that in turn increased the AC value of up to 0.191 $cm^3\ cm^{-3}$ and decreased the AWC value of down to 0.111 $cm^3\ cm^{-3}$ compared to loam, while 20w80b shows an opposite trend (Table 3). The AC values can be classified as medium to high, while the AWC values are at medium to low level. The Ks values between 40 cm d^{-1} and 79 cm d^{-1} can be classified as high without any significant changes compared to the loam.

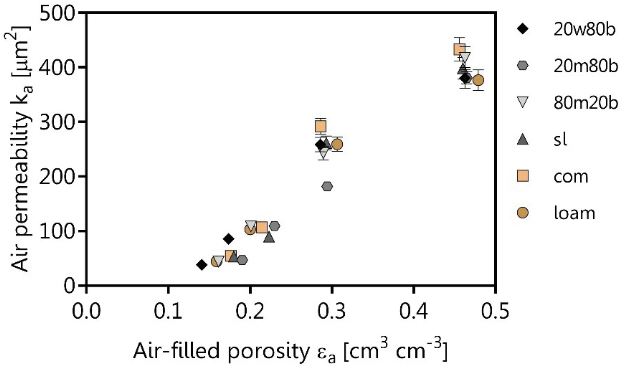

Figure 1. Air permeability, ka, obtained by Eq. 7 after the application of the organic residues for 8–10 soil cores each; abbreviations of residues are listed in Table 1.
Abbildung 1. Luftpermeabilität, ka, berechnet mit Gleichung 7 nach der Zuführung der organischen Rückstände für jeweils 8-10 Bodenproben; Abkürzungen sind in Tabelle 1 aufgeführt.

Table 3. Porosity, ε, air capacity, AC, plant available water capacity, AWC, and saturated hydraulic conductivity, Ks, after the application of the organic residues to the loam for 8–10 repeated measurements each. Differences in mean values compared to loam were significant at $p<0.05$ (*), $p<0.01$ (**), $p<0.001$ (***), and $p<0.0001$ (****) for ANOVA. The symbol ± corresponds to the standard deviation; abbreviations of residues are listed in Table 1.
Tabelle 3. Porosität, ε, Luftkapazität, AC, nutzbare Feldkapazität, nFK, und gesättigte Wasserleitfähigkeit, Ks, nach der Zuführung der organischen Rückstände zum Lehm mit jeweils 8-10 Messwiederholungen. Abweichungen zum Mittelwert des Lehms sind bei der ANOVA signifikant bei $p<0{,}05$ (*), $<0{,}01$ (**), $<0{,}001$ (***), $<0{,}0001$ (****). Das Symbol ± entspricht der Standardabweichung; Abkürzungen sind in Tabelle 1 aufgeführt.

Residues	**ε**	**AC**	**AWC**	**Ks**
	($cm^3\ cm^{-3}$)	($cm^3\ cm^{-3}$)	($cm^3\ cm^{-3}$)	(cm d^{-1})
Loam	0.462	0.142	0.143	54 ± 11
com	0.438	0.154	0.114**	58 ± 12
sl	0.439	0.151	0.122*	40 ± 14
80m20b	0.447	0.143	0.130	55 ± 21
20m80b	0.473	0.191***	0.111***	59 ± 23
20w80b	0.445	0.122	0.145	79 ± 31

In the range of ε_a values between 0.14 and 0.22 $cm^3\ cm^{-3}$, the k_a values are nearly identical, whereas the k_a values increase up to 433 μm^2 for compost (com) at the dry stage between ε_a values of 0.45 and 0.48 $cm^3\ cm^{-3}$ (Figure 1).

The c_2 and c_3 values in the range between −60 and −15,000 hPa show significant differences between the loam and the loam residue mixtures resulting in differences in pore size distribution and porosity continuity (Table 4). On the other side, the c_2 and c_3 values in the dry stage (105°C) are not very pronounced, resulting in a similar pore continuity and pore size distribution.

For better understanding of the model parameters, M, N, and ε_b, the k_a and ε_a values were fitted with Eq. 10 and ε_b was estimated with Eq. 11. The fitted parameters for loam and organic residue mixtures are listed in Table 5. A positive linear k_a/ε_a relationship (r^2: 0.96–0.99) was found, and the blocked air-filled pore space, ε_b, of the loam with 0.0079 $cm^3\ cm^{-3}$ was not significantly affected through the application of organic residue.

Table 4. Pore continuity indices c_2 and c_3 after the application of organic residues for 8–10 repeated measurements each at pressure heads, h, of –60, –300, and –15,000 hPa and in dry stage (105°C). Differences in mean values compared to loam were significant at $p<0.05$ (*), $p<0.01$ (**), $p<0.001$ (***), and $p<0.0001$ (****) for ANOVA. The symbol ± corresponds to the standard deviation, and r^2 indicates the coefficient of determination; abbreviations of residues are listed in Table 1.
Tabelle 4. Porenkontinuitätsindizes c_2 und c_3 nach der Zuführung der organischen Rückstände für jeweils 8-10 Messwiederholungen bei Druckstufen, h, von -60 hPa, -300 hPa, -15000 hPa und im getrockneten Zustand (105°C). Abweichungen zum Mittelwert des Lehms sind bei der ANOVA signifikant bei p<0,05 (*), <0,01 (**), <0,001 (***), <0,0001 (****). Das Symbol ± entspricht der Standardabweichung und r2 dem Korrelationskoeffizienten; Abkürzungen sind in Tabelle 1 aufgeführt.

	c_2 (μm²)				c_3 (μm²)			
Residue	–60 (hPa)	–300 (hPa)	–15,000 (hPa)	$dry_{105°C}$ (hPa)	–60 (hPa)	–300 (hPa)	–15,000 (hPa)	$dry_{105°C}$ (hPa)
Loam	341	533	953	904	2.147	2.667	3.110	1.888
com	214****	398***	903	835	1.215****	1.860****	3.155	1.831
sl	244****	485	828*	907	1.357****	2.176**	2.823	1.972
80m20b	290**	544	628****	823	1.799**	2.712	2.168****	1.781
20m80b	279**	390***	888	857	1.468****	1.697****	3.018	1.843
20w80b	315	592	906	814	2.237	3.412***	3.168	1.759

$dry_{105°C}$ = –1,000,000 hPa.

4. Discussion

4.1. Basic soil characteristics after application of organic residues

The results of the study presented in Table 2 indicate lower nitrogen contents, N_{total}, of 1.3 g kg^{-1} after the application of compost and sewage sludge compared to the digestates with N_{total} values between 1.5 and 1.6 g kg^{-1} through treatment-derived NH_3 and NH_4^+ losses (Möller and Müller, 2012; Stoknes et al., 2016). The nutrient contents (Na, K, Mg, and Ca) and, therefore, the cation exchange capacity, CEC_{pot}, were higher after the application of organic residues with values between 9.6 and 11.1 $cmol_c$ kg^{-1} than for the loam with 9.4 $cmol_c$ kg^{-1} as also proposed by Ojeda et al. (2015). The increase in pH values through the application of compost considering the initial pH of 8.1; thus, this liming effect was confirmed in several studies (Ojeda et al., 2015), also for other organic residues (e.g., biochar). The composition of organic matter was not directly investigated, but Tambone et al. (2010) proposed that the chemical composition did not greatly contribute to compare digestates with compost or sewage sludge. It should also be taken into account that the dose of the applied organic residues affects its use as soil conditioner and fertilizer each (Govasmark et al., 2011) and the additional supply of OC that contains different numbers of polar and non-polar functional groups can negatively affect the wettability of the loam. Thus, also the local connectivity of flow pathways is reduced (Beck-Broichsitter et al., 2020b). Furthermore, the potential risk of soil acidification after organic residue amendment (Voelkner et al., 2015a) and the effect on wettability and dispersion (Voelkner et al., 2015b) of aggregated structured soils compared to the initially homogenized loam used in this study should be validated under field conditions.

4.2. Effect of organic residue application on water retention characteristics and air permeability

The results presented in Table 3 indicate that the application of organic residues increased the ACs and decreased the plant AWC especially in case of digestate containing 20% maize and 80% sugar beet (20m80b). The results regarding the AWC values are contrary to the initial hypotheses and findings of Ojeda et al. (2015) and Beck-Broichsitter et al. (2018), except for digestate containing 20% wheat and 80% sugar beet, that slightly increased the AWC of the loam. Thus, the application of organic residues can potentially compensate low air capacities

Table 5. Model parameter, LogM, N, and blocked air-filled pore space, ε_b, after the application of organic residues for 8–10 repeated measurements each at pressure heads, h, of –60, –300, and –15,000 hPa and in dry stage (105°C). Differences in mean values compared to loam were significant at $p<0.05$ (*), $p<0.01$ (**), $p<0.001$ (***), and $p<0.0001$ (****) for ANOVA. The symbol ± corresponds to the standard deviation, and r2 indicates the coefficient of determination; abbreviations of residues are listed in Table 1.

Tabelle 5. Modellparameter, Log M, N, ans blockiertes Porenvolumen, ε_b, nach der Zuführung der organischen Rückstände für jeweils 8-10 Messwiederholungen bei Druckstufen, h, von -60 hPa, -300 hPa, -15000 hPa und im getrockneten Zustand (105°C). Abweichungen zum Mittelwert des Lehms sind bei der ANOVA signifikant bei p<0,05 (*), <0,01 (**), <0,001 (***), <0,0001 (****). Das Symbol ± entspricht der Standardabweichung und r2 dem Korrelationskoeffizienten; Abkürzungen sind in Tabelle 1 aufgeführt.

Residue	**LogM**	**N**	ε_b	r^2
	(–)	(–)	(cm^3 cm^{-3})	(–)
Loam	121	1.200	0.0079	0.96
com	158***	1.231	0.0074	0.99
sl	180****	1.328	0.0073	0.98
80m20b	121	1.081	0.0077	0.99
20m80b	175****	1.276	0.0072	0.97
20w80b	75****	1.017*	0.0084	0.98

(Jasinska et al., 2006), whereas the decrease in AWC values can be attributed to the decrease in volume fraction of medium pores (-300 < h < -15,000 hPa) through homogenization as stated by Hu et al. (2009). However, wheat-containing digestate (20w80b) seems to slightly improve or not deteriorating the AWC as hypothesized before. It should be noted that the increase in the air capacities indicates an increase in the volume fraction of pores available for air flow or soil aeration, but it is not identical with the accessibility of oxygen for plant roots (Reszkowska et al., 2011; Beck-Broichsitter et al., 2020a).

The application of organic residues, however, significantly lowered the pore continuity at pressure heads of –60 and –300 hPa, except digestate 20w80b. The air-filled coarse pores may not contribute to the flow when they are discontinuous (Lipiec et al., 2003; Dörner and Horn, 2006). In the dry stage, the pore continuity indices presented in Table 4 show no significant differences; thus, the formation of shrinkage cracks seems to become more important for the connectivity of the pore system (Beck-Broichsitter et al., 2020b). However, compared to aggregated, structured soils in the field, the initially homogenized samples in this study tend to a higher shrinkage crack formation potential (Beck-Broichsitter et al., 2018) resulting in a comparatively higher air-filled porosity, more pronounced preferential flow paths and, therefore, overestimated air permeabilities. By the way, the slope factor N derived by Eq. 10 was significantly lower for digestate 20w80b than for loam and other residues; thus, the pore connectivity increases slowly with increase in air-filled pore porosity (Ball et al., 1988).

The blocked air-filled porosities presented in Table 5, between 0.0072 and 0.0084 cm^3 cm^{-3}, are nearly equal and on a very low level compared to the porosities in Table 2; thus, almost all pores of loam and loam residues mixtures are available for gas flow as also proposed for tilled topsoils (Dörner et al., 2012). This may be related to the increase in OC content that contributes a better quality of porous media (Assis et al., 2016). On the other side, tillage-induced homogenization can interrupt the functional pore system (Petersen et al., 2008), and compared to non-tillage conditions, the blocked air-filled porosity could be higher (Dörner and Horn, 2006; Dörner et al., 2012). In terms of the study results, the initial re-compaction of the soil cores to 1.45 g cm^{-3} may positively affected the rearrangement of the soil particles and pore connectivity (Horn et al., 2014) that could be another reason for the very low ε_b values.

5. Conclusion

The objective of the study was to determine the effect of application of compost, sewage sludge, and digestates containing maize, sugar beet, and winter wheat on nutrient content, air capacity, plant available water capacity, and air permeability.

The results suggest that the application of organic residues can increase the nutrient content (Na, K, Mg, and Ca) and the air capacity of the loamy soil, whereas the plant available water capacity and the pore continuity may decrease. It can also not be concluded that a higher air capacity automatically increases the pore continuity and, therefore, the air permeability. However, the wheat-containing digestate 20w80b shows an opposite trend, slightly improving the plant available water capacity, whereas the air capacity is significantly lower compared with compost, sewage sludge, maize-containing digestates, and the untreated loam.

Further research is needed to investigate the application of organic residues under field conditions considering tilled and non-tilled conditions.

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Conflict of interest

We have no conflict of interest to declare.

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