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Anisotropy of subsoil pore characteristics and hydraulic conductivity as affected by compaction and cover crop treatments

Mansonia Pulido-Moncada[1] | **Rodrigo Labouriau**[2] | **Merek Kesser**[1,3] | **Pedro Paulo Gonçalves Zanini**[4] | **Rachel Muylaert Locks Guimarães**[4] | **Lars J. Munkholm**[1]

[1] Department of Agroecology, Research Centre Foulum, Aarhus Univ., Blichers Allé 20, P.O. Box 50, Tjele DK-8830, Denmark

[2] Department of Mathematics, Applied Statistics Laboratory, Aarhus Univ., Ny Munkegade 118, Aarhus, Denmark

[3] School of Agriculture, Food & Wine, Waite Research Institute, The Univ. of Adelaide, PMB 1, Glen Osmond, SA 5064, Australia

[4] Departamento de Ciências Agrárias, Univ. Tecnológica Federal do Paraná, Via do Conhecimento, km 1, Pato Branco, PR 85503-390, Brazil

Correspondence

Las J. Munkholm Department of Agroecology, Research Centre Foulum, Aarhus University, Blichers Allé 20, P.O. Box 50, Tjele, DK-8830, Denmark

Email: Lars.munkholm@agro.au.dk

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Abstract

The natural and cover crop (CC)-induced anisotropy of subsoil pore characteristics is important in assessments of soil compaction but, until recently, has received limited attention. This study aims to quantify the anisotropy of soil pore characteristics and hydraulic conductivity in subsoils subjected to compaction and CC treatments in a split-plot field experiment on temperate sandy loam soils. The main factor was ±compaction and the split-plot factor was ±CC with fodder radish (*Raphanus sativus* L.). The compacted plots were heavily trafficked for 4 yr (2010–2013). After 4 yr under CC (2013–2016), core samples were collected at 0.3 m. The samples were taken vertically and horizontally to quantify the anisotropy of air-filled porosity (ε_a) and air permeability (k_a), saturated hydraulic conductivity (k_{sat}), and bulk density (ρ_b). The results showed isotropic behavior for ρ_b and ε_a and significant anisotropic behavior ($p < .05$) for k_a, pore geometry index (PO1) (k_a/ε_a), ratio of non-Darcian to Darcian k_a (R-ratio), and k_{sat}. For parameters with significant anisotropy, higher values occurred vertically than horizontally for all compaction –CC combinations, except for R-ratio. This indicates that pre-existing vertical continuous pores dominated the pore system in the control subsoil. A nonsignificant trend of higher values of k_a, PO1, and k_{sat} in the +CC than in the compacted –CC plots suggest that CC could contribute to the formation of vertical biopores. Including an autumn CC in rotation with a summer cereal crop for a longer period may significantly affect the anisotropy of the soil pore and hydraulic properties.

1 | INTRODUCTION

Soil is a heterogeneous natural body characterized by variations in its properties at the landscape scale (horizontal plane) and the soil profile (vertical plane) (Bathke & Cassel, 1991). At a given spatial point, the measurements of soil properties can also change depending on the direction of the measurements, which is defined as soil anisotropy (Pozdnyakov,

Abbreviations: CC, cover crop; k_a, Darcian permeability; $k_{a\text{-}5hPa}$, non-Darcian permeability at 5 hPa pneumatic pressure; k_{sat}, soil saturated hydraulic conductivity; *PO1*, pore geometry index (k_a/ε_a); R-ratio, ratio of non-Darcian to Darcian air permeability; ε_a, volume of air-filled porosity; ρ_b, soil dry bulk density.

Rusakov, Shalaginova, & Pozdnyakova, 2009). This definition implies that to measure the gradients of change in a given soil property, measurements should be taken in both the horizontal and vertical directions. Hence the ratio of measurements between the directions (horizontal or vertical) can be used to characterize the degree of anisotropy.

The anisotropy of soil physical properties in a soil horizon results from a combination of natural and anthropogenic factors. In agricultural soils, different management practices such as tillage and field traffic may contribute to anisotropy (Peng, 2011). Some of the causes of a direction-dependent soil parameter are soil layering (Assouline & Or, 2006; Deng & Zhu, 2015), the rearrangement of soil aggregates (Reszkowska, Krc›mmelbein, Gan, Peth, & Horn, 2011), the presence of biopores (Germer & Braun, 2015), cracks induced by soil shrinkage and swelling (Peng & Horn, 2007), and the formation of a plough pan layer and platy structures caused by compaction (Dörner & Horn, 2009; Peng, 2011).

Subsoil compaction affects soil physical properties as a consequence of the development of the direction-dependent behavior of the pore system (Dörner & Horn, 2009). Changes in the soil pore anisotropy of agricultural soils directly impact water transport and storage, soil–atmosphere gas exchange, and soil aeration (Berisso et al., 2013; Soracco et al., 2015). Air permeability and saturated hydraulic conductivity have been found to show anisotropic behavior caused by changes in the geometry and continuity of the pore system resulting from compaction (Dörner & Horn, 2006), although other authors have not detected any changes to the anisotropy of air permeability and pore geometry after compaction of the subsoil layer (Obour, Schjønning, Peng, & Munkholm, 2017).

Trends for horizontal or vertical directional preferences have been reported for some soil properties. For instance, hydraulic conductivity was described as being greater in the horizontal direction than in the vertical direction after compaction because of the preferential orientation of platy structures (Dörner & Horn, 2009). The opposite anisotropic behavior was apparent in compacted layers with a massive structure containing earthworm burrows (Kulli, Gysi, & Flühler, 2003) and in well-structured soils (Bathke & Cassel, 1991), where vertical pores are typically more continuous than horizontal pores because of the biological activity of soil organisms and plant roots (Soracco et al., 2015). The soil strength of heavily trafficked soils has been found to be larger in the vertical direction than in the horizontal direction (Peng & Horn, 2008). The preferential direction of soil properties is reported, however, to vary depending on anthropogenic factors such as tillage methods (Kühne, Schack-Kirchner, & Hildebrand, 2012) and also on the dynamic nature of soil structure (Petersen, Trautner, & Hansen, 2008).

The study of soil anisotropy and its changes may contribute to the evaluation and monitoring of the status of soil properties for crop production (Berisso et al., 2013). Specifically, soil anisotropy is useful for assessing the existence and effects of pathways for the migration of substances in the soil profile (Pozdnyakov et al., 2009), which is of interest for modeling transport phenomena in the soil (Petersen et al., 2008). Additionally, the study of soil anisotropy can provide an understanding of the degree of soil degradation and recovery processes (Reszkowska et al., 2011). As traffic load-induced changes to soil structural properties persist for decades and recover slowly in the subsoil, the degree of anisotropy could be used as a sensitive indicator to monitor the structural recovery processes of compacted subsoil (Peng & Horn, 2008).

Core Ideas

- The preferentially vertical dynamic soil properties were independent of compaction.
- Tubular continuous vertical pores dominated the pore system in agricultural subsoil.
- The cover crop slightly improved soil gas and water transport in compacted subsoils.

The use of deep-rooted cover crops as biosubsoilers has been proposed as a measure to mitigate soil compaction (Chen & Weil, 2010; Rosolem & Pivetta, 2017). The beneficial effects of biosubsoilers on hard layers are associated with the creation of root channels or biopores and the consequent cracking or fissures (Han et al., 2015; Materechera, Alston, Kirby, & Dexter, 1992). The biopores that persist after root decay or earthworm burrowing boost the functionality of the soil pore system by enabling gas and water flow (Cresswell & Kirkegaard, 1995; Holtham, Matthews, & Scholefield, 2007; Kautz, 2015), which is of major importance, especially in compacted subsoils. Taprooted crops, such as fodder radish (*Raphanus sativus* L.), have the ability to create continuous, deep, vertical biopores, which may be used as preferential pathways by subsequent roots (Williams & Weil, 2004) and by gas, water, and solutes (Çerçioğlu, Anderson, Udawatta, & Alagele, 2019; Fageria, Baligar, & Bailey, 2005). Therefore, biopores are expected to play an essential role in the anisotropy of soil physical properties of compacted soils. There is, however, a paucity of knowledge on the effects of cover crops on direction-related changes in soil structural properties.

This study aims to evaluate (i) the influence of subsoil compaction on the anisotropic behavior of soil pore characteristics and hydraulic conductivity and (ii) the use of a fodder radish cover crop to mitigate subsoil compaction.

We hypothesized that compaction would increase the degree of anisotropy of the soil pore characteristics and hydraulic conductivity, through the increased dominance of vertically oriented pores. It was also expected that the cover crop would mitigate soil compaction and change the anisotropic behavior of the measured soil parameters.

2 | MATERIALS AND METHODS

2.1 | Study site

The study was conducted in Aarslev (55˚18′18″N, 10˚26′52″E) and Flakkebjerg (55˚19′42″N, 11˚24′28″E), Denmark, as part of a compaction mitigation study after four consecutive years of realistic heavy farm traffic (Schjønning, Lamandé, Munkholm, Lyngvig, & Nielsen, 2016). The soils at both sites are sandy loams classified as Orthic Luvisols (World Reference Base for Soil Resources classification system).

At the Aarslev site, the 0- to 0.25-m soil layer is characterized by 127, 136, and 737 g kg^{-1} of clay (<2 μm), silt (2–20 μm), and sand (20 μm–2 mm), respectively, and 21 g kg^{-1} of soil organic matter; the 0.25- to 0.5-m depth by 173, 132, 695, and 7 g kg^{-1} of clay, silt, sand, and soil organic matter, respectively. At the Flakkebjerg site, the clay, silt, sand, and soil organic matter contents are 152, 129, 719, and 21 g kg^{-1}, respectively, at 0 to 0.25 m and 169, 123, 708, and 12 g kg^{-1}, respectively, at 0.25 to 0.50 m (Schjønning et al., 2016).

At Aarslev, 6 yr prior to the initiation of the compaction trial, the site was mechanically subsoiled to a depth of 0.40 m (Schjønning et al., 2016). No subsoiling was registered for the Flakkebjerg site.

2.2 | Experimental treatments

Two treatment factors were included in the experiment established at Aarslev and Flakkebjerg, namely compaction and a cover crop (CC). The field experiments were designed in a split-plot arrangement with four replicates. The main treatment was compaction, which was conducted before the CC treatments were carried out. The compaction experiment, conducted from 2010 to 2013, consisted of two treatments (control and compacted), with experimental plots measuring 10 by 30 m. The control treatment was not experimentally trafficked. In the compacted treatment, the entire experimental area was subjected to four-wheel passages by a tractor–trailer combination with an 8-Mg (78 kN) wheel load (denoted M8). The tire inflation pressure of the tractor was between 150-300 and 170-290 kPa for Aarslev and Flakkebjerg, respectively, and the range of mean ground pressure was between 56-161 and 49-152 kPa, respectively. Both the control and compacted experimental plots were ploughed annually and the experimental traffic was applied at a soil water content near field capacity. Further details about the compaction experiments can be found in Schjønning et al. (2016).

Spring barley (*Hordeum vulgare* L.) was sown every year from 2010 to 2016 in both the control and compacted treatments of the main plots in early spring and harvested in midsummer. In August 2013, immediately following the harvest of spring barley, the main plots were split so that one half was sown with fodder radish (*R. sativus* cv. Adagio) (+CC treatment), whereas the other half of the plot was left without a fodder radish (–CC), resulting in four treatment groups: compacted +CC, compacted –CC, control +CC, and control –CC. Fodder radish was sown every year (2013-2016) at a seeding rate of 10 kg ha^{-1} with very shallow (∼5 cm) tillage with a standard seed drill and fertilized with 30 kg N ha^{-1}. The fodder radish was ploughed into the soil each year in late autumn.

2.3 | Soil samples

A previous study indicated that after 2 yr of the compaction treatment in the same experimental plots, the highest values of field penetration resistance were recorded at ∼0.30 m depth at both field sites (i.e., 1.5 and 1.2 MPa at Aarslev and Flakkebjerg, respectively) for the control treatment and 2.4 and 1.5 MPa for the compacted treatment (Schjønning et al., 2016). Additionally, at the sampling time in the present study (2017), negative effects of compaction on bulk density, air volume, and gas transport were found at 0.3- to 0.5-m depth for both Aarslev and Flakkebjerg (Pulido-Moncada, Schjønning, Labouriau, & Munkholm, 2020b). Therefore, the most compacted layer in both of the field sites was identified at 0.3-m depth, which was thus our focus of interest for the present study.

Two years after completing the compaction experiment in 2015, samples were collected from Aarslev in the subplots without a CC to quantify the effect of soil compaction. In 2017, sampling was conducted in all the treatments at Aarslev and Flakkebjerg to evaluate the use of fodder radish as a potential biosubsoiler.

For each sampling campaign, three sampling points were randomly selected 2 m from the plot border. Minimally disturbed soil samples were collected at each sampling point with metal cylinders (9.6 cm width, 8.0 cm height) in both the vertical and horizontal directions at 0.3 m depth (compacted layer).

At Aarslev in 2015, 48 samples were collected (two treatments, four replicates, three sampling points, and two sampling directions), whereas in 2017 at both sites, the same sampling scheme was followed in both of the split-plots, giving a total of 96 samples for each site. Soil cores were stored at 2 ˚C until laboratory measurements and analysis.

2.4 | Laboratory measurements and analyses

The undisturbed soil cores were saturated and then drained to –100 hPa matric potential before being measured for air permeability (k_a) and air-filled porosity (ε_a). The Darcian air permeability (k_a) and the non-Darcian air permeability measured at a pneumatic pressure of 5 hPa (k_{a_5hPa}) were measured via the Forchheimer approach using an apparatus that allows for automatic measurement of airflow at a range of pneumatic pressures (Schjønning & Koppelgaard, 2017).

An air pycnometer (Hammershøj Maskinteknik, Tjele, Denmark) was used to measure the fraction of air-filled soil porosity connected to the atmosphere (ε_a) (Flint & Flint, 2002; Rüegg, 2000).

Soil saturated hydraulic conductivity (k_{sat}) measurements were conducted after pore characterization. The k_{sat} was determined via the constant-head method (Klute & Dirksen, 1986) with a laboratory permeameter made in-house that was filled with 0.01 M $CaCl_2$ solution to a hydraulic head of 1.5 cm. The falling-head method of measuring k_{sat} was conducted as an alternative to the constant-head method (Klute & Dirksen, 1986) when the samples were very heavily compacted and conductivity was null after 5 h under the constant-head method.

The soil cores were then oven-dried at 105 ˚C to calculate soil dry bulk density (ρ_b) from the dry mass of each soil core.

The pore geometry index (PO1) suggested by Groenevelt, Kay, and Grant (1984) (Equation 1) and the ratio of non-Darcian to Darcian air permeability (R-ratio) proposed by Schjønning et al. (2013) (Equation 2) were also calculated.

$$\mathrm{PO1} = \frac{k_a}{\varepsilon_a}; \quad (1)$$

$$R = \frac{k_{a-5hPa}}{k_a}. \quad (2)$$

The degree of anisotropy of each of the soil physical parameters was calculated to detect if there were differences in the measurement values that depended on the direction of the soil samples (Pozdnyakov et al., 2009):

$$P_{H/V} = \frac{P_H}{P_V}, \quad (3)$$

where $P_{H/V}$ is the degree of anisotropy of a measured parameter, P_H is the value of the measured parameter in the horizontal direction, and P_V is the value of the measured parameter in the vertical direction. Anisotropy was considered to exist if $P_{H/V}$ was significantly different from 1.

2.5 | Statistical analyses

Analysis of the residuals was used to check whether the assumptions of mixed model were satisfied. In all cases, a Gamma model was used, except for ρ_b and ε_a which were modeled via a standard Gaussian model (i.e., a model based on the normal distribution). In all the models, a logarithmic link function was used so that the differences in the effects, measured in the logarithmic scale and back-transformed via the exponential, were the ratios between the horizontal and the vertical parameters. Estimation of the parameters was conducted for each combination of treatment (control and 8 Mg wheel load) and direction. The models contained three random components, representing the block, the subparcel (treatment × block), and the sampling point (nested within the subparcel). All the models used were carefully controlled and tested. In the 2017 data, the cover crop effect was added to the models. The analyses were performed in R software (R Core Team, 2020) and the R statistical packages R lme4 (Bates, Mächler, Bolker, & Walker, 2014) and postHoc (Labouriau, 2020) both available on CRAN. All tests were conducted at the 5% significance level. The confidence intervals of the soil parameter means are shown in Supplemental Table S1.

3 | RESULTS AND DISCUSSION

3.1 | Bulk density and air-filled porosity

In the vertical direction, compaction increased ρ_b regardless of the CC treatment at both sites ($p < .05$) (Table 1). In the horizontal direction, the highest ρ_b was also found for the compacted soil. There was, however, also a significant interaction between compaction and CC for both soils in the horizontal direction, with the highest ρ_b in the compacted –CC soils at both sites and the lowest ρ_b in the control –CC soil at Aarslev and the control +CC soil at Flakkebjerg.

The ε_a was found to decrease in the order: control –CC > control +CC > compacted (±CC) in both the vertical and horizontal directions at Aarslev (Table 1). At Flakkebjerg, there was also a trend of the highest ε_a occurring in the control treatments, though it was nonsignificant at $p = .05$.

The general observed increase in ρ_b and decrease in ε_a as a consequence of subsoil compaction was consistent with previous results from the same experiments (Obour et al., 2017; Pulido-Moncada, Munkholm, & Schjønning, 2019) and with the findings of other studies (Arvidsson, 2001; Kuncoro, Koga, Satta, & Muto, 2014). Unlike the compaction treatment, the lack of a CC effect on the ρ_b and ε_a of compacted subsoils is contrary to the compaction mitigation effect of CCs reported in other studies (Cresswell & Kirkegaard, 1995; Kautz, Stumm, Kösters, & Köpke, 2010; Raper, Reeves,

TABLE 1 Dry bulk density (ρ_b) and air-filled porosity (ε_a) at –100 hPa, measured in the horizontal and vertical directions from Aarslev and Flakkebjerg sites, 4 yr after the sowing of fodder radish as a cover crop (CC)

Treatment		ρ_b H[a]	ρ_b V	ρ_b	ε_a H	ε_a V	ε_a
		Mg m^{-3}		*H/V*	m^3 m^{-3}		*H/V*
Aarslev 2017							
Control	+CC	1.74[b] b	1.71 a	1.02 b ns	0.10 a	0.10 ab	0.98 a ns
	–CC	1.68 a	1.71 a	0.98 a ns	0.15 b	0.13 b	1.16 a ns
Compacted	+CC	1.78 bc	1.82 b	0.98 a ns	0.07 a	0.07 a	1.10 a ns
	–CC	1.82 c	1.85 b	0.98 a ns	0.06 a	0.04 a	1.33 a ns
Flakkebjerg 2017							
Control	+CC	1.71 a	1.74 a	0.99 a ns	0.11 a	0.10 a	1.17 a ns
	–CC	1.72 ab	1.76 a	0.98 a ns	0.11 a	0.09 a	1.32 a ns
Compacted	+CC	1.80 bc	1.84 b	0.98 a ns	0.08 a	0.07 a	1.09 a ns
	–CC	1.84 c	1.85 b	0.99 a ns	0.07 a	0.05 a	1.22 a ns

*Significantly different from 1. ns, not significantly different from 1.
[a]H, horizontal direction; V, vertical direction; *H/V*, degree of anisotropy. [b]Values in a column followed by the same lowercase letters are not significantly different among factor combinations (treatment and cover crop).

Burmester, & Schwab, 2000; Williams & Weil, 2004), yet there are many different factors that could contribute to this finding. For example, Welch, Behnke, Davis, Masiunas, and Villamil (2016) also showed that fodder radish did not significantly alleviate after 2 yr in compacted headlands in organic systems in Illinois. The author attributed this to the combination of factors such as soil resilience, climate, and the duration of the CC. It is possible that similar factors affected the outcome of our study, particularly the relatively short growing season for fodder radish under Danish conditions (typically 2–3 mo). Therefore, it may take more than 4 yr for the fodder radish CC to impact bulk soil physical properties significantly in severely compacted subsoils in Denmark. This was previously discussed for the results from the same experiments on samples with a smaller soil volume of 100 cm^3 taken in the vertical direction (Pulido-Moncada et al., 2020b).

The degrees of anisotropy for ρ_b and ε_a were not significantly different from 1 for both the Aarslev and Flakkebjerg sites and did not differ among treatments (Table 1). These results are consistent with previous findings for the isotropic behavior of ρ_b and ε_a (Kuncoro, Koga, Kanayama, & Muto, 2015).

3.2 | Air permeability and morphological pore characteristics

At the Aarslev site, k_a was found to be smaller for compacted than for control soils in both directions ($p < .05$), though in the vertical direction, the control –CC treatment was not significantly different from the compacted +CC treatment (Table 2). At Flakkebjerg, a smaller k_a value was found for the compacted –CC soil than for the other combinations of compaction and CC treatments in the vertical direction ($p < .05$), whereas there were no significant differences among treatments in the horizontal direction. Pulido-Moncada et al. (2020b) also reported a compaction effect on k_a from 100-cm^3 samples taken in the vertical direction at Aarslev and Flakkebjerg in the same year of evaluation. Reductions in k_a have been shown to reflect a disruption of connected porosity and a decrease in the volume of macropores (Mossadeghi-Björklund et al., 2016).

The k_a values for the compacted +CC soil were similar to the control –CC soil in the vertical direction, suggesting a CC-induced recovery of pore functionality in the compacted subsoil. A positive CC effect, reflected in increasing k_a values in the topsoil layer, has been reported in a number of studies (Abdollahi, Munkholm, & Garbout, 2014; Chen, Weil, & Hill, 2014; Steele, Coale, & Hill, 2012). Information on cover crop-related subsoil pore functionality is less prevalent, although taprooted crops such as lucerne (*Medicago sativa* L.) have been shown to increase the connected air-filled porosity in the subsoil (Uteau, Pagenkemper, Peth, & Horn, 2013).

There was a nonsignificant trend for k_a values to be larger in the vertical than in the horizontal direction for the compacted +CC ($p = .06$) and –CC ($p = .08$) soils at Aarslev (Table 2). At Flakkebjerg, k_a was significantly anisotropic for all treatments ($p < .05$), with higher measurements in the vertical than in the horizontal direction, except for the compacted –CC treatment. The degree of anisotropy was not significantly different among treatments at either site.

The significant anisotropic behavior of k_a at –100 hPa for the Flakkebjerg subsoil, indicating greater values in the vertical than in the horizontal directions, was in agreement with

TABLE 2 Air permeability (k_a), pore geometry index (PO1), the ratio of the non-Darcian to Darcian air permeability (R), and saturated hydraulic conductivity (k_{sat}) from the Aarslev and Flakkebjerg sites 4 yr after the sowing of fodder radish as a cover crop (CC). Measurements were conducted at –100 hPa matric potential

Treatment		k_a H[a]	k_a V	k_a	PO1 H	PO1 V	PO1	R H	R V	R	k_{sat} H	k_{sat} V	k_{sat}
		—µm²—		*H/V*	—µm²—		*H/V*			*H/V*	cm d^{-1}		*H/V*
Aarslev 2017													
Control	+CC	11.2[b] b	16.6 c	0.68 a ns	96.7 a	192.7 a	0.50 ab *	0.86 a	0.74 a	1.15 a *	56.3 b	156.1 a	0.36 a ns
	–CC	13.9 b	11.6 bc	1.20 a ns	79.6 a	100.0 a	0.80 b ns	0.88 ab	0.81 ab	1.08 a ns	12.1 ab	38.2 a	0.32 a ns
Compacted	+CC	3.1 a	6.1 ab	0.51 a ns	88.2 a	195.7 a	0.45 ab*	0.93 ab	0.82 ab	1.13 a *	7.4 a	123.3 a	0.06 a*
	–CC	2.0 a	4.3 a	0.47 a ns	67.9 a	550.5 b	0.12 a*	0.97 b	0.85 b	1.15 a*	11.8 ab	64.1 a	0.18 a*
Flakkebjerg 2017													
Control	+CC	10.7 a	36.5 b	0.29 a*	72.3 a	406.2 b	0.18 a*	0.91 a	0.68 a	1.35 a*	68.7 b	418.8 b	0.16 a*
	–CC	8.4 a	26.8 b	0.32 a*	67.7 a	320.0 ab	0.21 a*	0.91 a	0.81 b	1.11 a ns	98.8 b	296.0 b	0.33 a ns
Compacted	+CC	9.7 a	25.1 b	0.39 a*	76.8 a	434.0 b	0.18 a*	0.94 a	0.77 ab	1.22 a*	34.8 ab	246.9 b	0.14 a*
	–CC	5.0 a	5.9 a	0.86 a ns	68.2 a	179.3 a	0.38 a*	0.94 a	0.87 b	1.08 a ns	17.1 a	75.0 a	0.23 a*

*Significantly different from 1. ns, not significantly different from 1.
[a] *H*, horizontal direction; V, vertical direction; *H/V*, degree of anisotropy.
[b] Values in a column followed by the same lowercase letters are not significantly different among factor combination (treatment and CC).

the results by Kuncoro et al. (2015). Conversely, in a study on a sandy clay loam soil in Sweden, Berisso et al. (2013) found anisotropic k_a measurements (vertical > horizontal) for noncompacted subsoil but not for compacted subsoil at –100 hPa at 0.3-m depth. As soil compaction reduces the size of the effective pores for airflow (Schäffer et al., 2008), it is important to note that the anisotropy of k_a has been reported to vary with matric potential, which is the result of the degree of connectivity of different pore sizes (Dörner & Horn, 2009).

The higher k_a in the vertical direction observed in the present study could be explained by the greater degree of closing in horizontal pores than in vertical pores as a consequence of vertical mechanical stress during compaction (Kühne et al., 2012; Schäffer et al., 2008). Previous results from compaction experiments have also indicated that compaction causes vertical pores to have a more dominant role for airflow (Schjønning, Pulido-Moncada, Munkholm, & Iversen, 2019).

The pore geometry index (PO1) was, in general, significantly anisotropic for both sites, as indicated by the larger PO1 in the vertical than in the horizontal direction ($p \leq .05$), except for the control –CC treatment at Aarslev (Table 2).

The lower PO1 obtained in the horizontal direction, related to the lower k_a, indicates less continuous and more tortuous large pores in the horizontal than in the vertical direction, as was also found by Kuncoro et al. (2015). Although the degree of anisotropy of PO1 did not significantly differ among treatments, it tended to be lower in the +CC plots, except in the compacted Aarslev soil, which suggests the creation of more vertical pores by fodder radish roots.

The similar magnitude of anisotropy found among treatments for k_a and PO1 indicates that before compaction, airflow mainly happened through vertical pores, which were then reduced in volume after compaction but remained functional for airflow (Schäffer et al., 2008). This finding supports the characterization of agricultural subsoils advanced by the conceptual model of Arah and Ball (1994) and confirmed by Lamandé, Schjønning, Dal Ferro, and Morari (2020), namely that they are dominated by vertical (bio)pores that govern the air transport.

Figure 1 shows that for both sites, no apparent difference among treatments can be observed from the ratio of $k_{a\text{-}5hPa}$ to k_a. In the vertical direction, the k_a tended to be larger than the $k_{a\text{-}5hPa}$ at higher levels of permeability (k_a > 10 µm^2), as shown by a progressive deviation from the 1:1 line at both sites. This interpretation is discussed below. In previous studies from the same experiment, smaller vertically oriented samples (100 cm^3) showed increasing deviation between the two estimates of air permeability with increasing levels of permeability (Pulido-Moncada et al., 2020b; Schjønning et al., 2019). In those studies, the measured range of air permeability was larger (0.01–1000 µm^2) than those obtained in the present study (0.01–100 µm^2), which may be related to the sample scale.

The R-ratio at k_a < 100 µm^2 was significantly higher for the compacted –CC treatment than for the control +CC treatment in both sampling directions in the Aarslev soil but only in the vertical direction at Flakkebjerg (Table 2). This suggests that soil compaction reduced the impact of large continuous macropores for the studied 579-cm^3 cores. This result does not agree with our previous studies on 100-cm^3 cores, where a negative compaction effect was evident with a decreasing R-ratio at k_a > 32 µm^2, showing that compaction increased

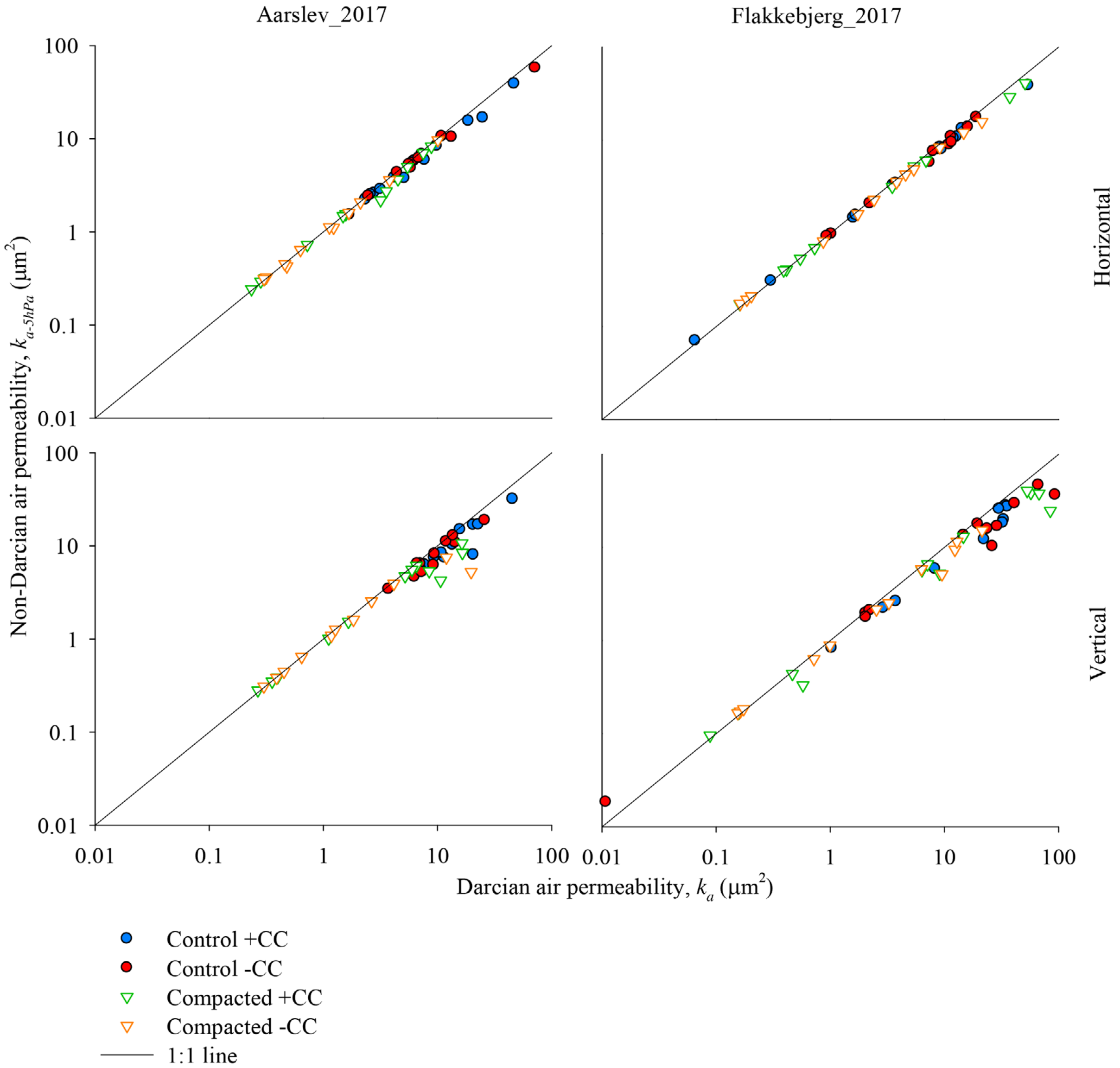

FIGURE 1 Relationship non-Darcian to Darcian air permeability at Aarslev and Flakkebjerg sites 4 yr after the sowing of fodder radish as a cover crop (CC). Measurements were conducted at –100 hPa matric potential on samples taken in the horizontal and vertical directions

the dominance of large continuous biopores. In the present study, partitioning the data to enable the compaction effect to be evaluated at different levels of air permeability (e.g., $k_a > 32$ μm²) was not possible, as each range had a number of observations.

In general, the *R*-ratio was significantly smaller in the vertical direction than in the horizontal (as can be observed in Figure 1). The degree of anisotropy of the *R*-ratio did not differ among treatments, although a nonsignificant tendency for the *R*-ratio to be smaller in the vertical direction was observed for +CC plots (Table 2). This may suggest that the fodder radish cover crop generally increased preferential airflow through the formation of biopores (Dörner & Horn, 2009).

For our studied 579-cm³ cores, the air-filled pore volume did not vary between the horizontal and vertical sampling directions. As such, differences in air transport measurements between sampling directions are expected to be related to differences in pore characteristics such as continuity, connectivity, geometry, and size distribution. The trend towards larger k_a and smaller *R*-ratio values in the vertical than in the horizontal direction suggest that there is more turbulence in this direction, as the vertical pore system is dominated by pores with greater continuity (Schjønning et al., 2019). Our results indicate that the airflow pores in the horizontal direction are dominated by planar pores with only little turbulence and dead-end cracks, which is reflected in the lower PO1 (k_a/ε_a) values (Maier et al., 2012) than in the vertical direction.

The average air pore velocity was calculated from the superficial air velocity at 5 hPa divided by the fraction of ε_a (Schjønning et al., 2019) and plotted to the *R*-ratio obtained

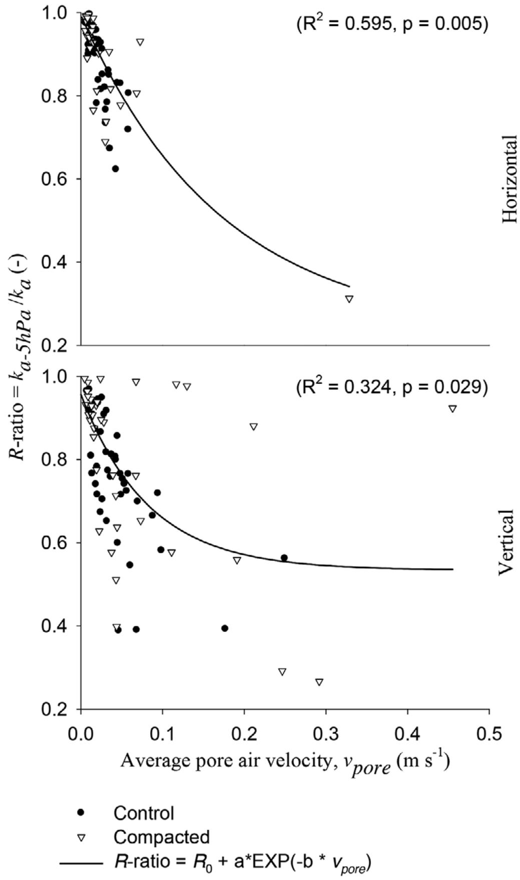

FIGURE 2 The relationship between the ratio of non-Darcian ($k_{a\text{-}5hPa}$) to Darcian (k_a) air permeability (*R*-ratio) and the average pore air velocity (v_{pore}) at –100 hPa matric potential for samples taken in the horizontal and vertical directions at both the Aarslev and Flakkebjerg sites. The relationship between the *R*-ratio and air velocity was described by the exponential model suggested by Schjønning et al. (2019)

for each sampling direction (Figure 2). This relationship showed that the *R*-ratio decreased with increasing pore air velocity in both sampling directions, as demonstrated previously by Schjønning et al. (2013, 2019). Importantly, there were larger values of air pore velocity in the vertical direction than in the horizontal direction ($p < .05$), which were probably caused by vertically oriented biopores. This supports the concept that in compacted subsoils, gas transport is governed by the characteristics of the bio-pores rather than by the air-filled pore volume per se (Pulido-Moncada et al., 2019; Schjønning et al., 2013).

3.3 | Saturated hydraulic conductivity

The k_{sat} values were significantly smaller for the compacted –CC treatment than for the control soils in the vertical and horizontal direction at the Flakkebjerg site ($p < .05$) (Table 2). At the Aarslev site, the negative compaction effect, reflected in the decreasing k_{sat}, was only significant within the +CC plots in the horizontal direction. Anisotropic water transport was found for the two sites, as significantly larger k_{sat} values were measured in the vertical than in the horizontal direction ($p < .05$; $p = .07$ for control –CC in Flakkebjerg), except for the control soils in Aarslev, which were generally more isotropic.

The results are in agreement with other studies. A study on forest soil in Austria, for example, demonstrated that the vertical k_{sat} was naturally larger than in the horizontal direction (Germer & Braun, 2015). However, the opposite trends have been demonstrated after compaction, where larger k_{sat} values were measured in the horizontal direction than in the vertical direction by Dörner and Horn (2009), probably because of the compaction-induced disruption of continuous unstable vertical pores.

In our study, the anisotropic behavior of k_{sat}, as in the case of k_a, was probably caused by the tube-like arrangement of the large pores in the vertical direction and the reduction of continuous pores in the horizontal direction of the subsoil layer. Large pores mainly govern the water flow when the soil is saturated (Iversen, Moldrup, Schjønning, & Jacobsen, 2003). In this regard, Kim, Anderson, Motavalli, and Gantzer (2010) found, by using X-ray computed tomography, that macroporosity may explain up to 80% of the variability in the k_{sat} of both compacted and noncompacted soils. Therefore, changes in macropores or large vertical pores might directly affect the k_{sat} status (Alaoui, Lipiec, & Gerke, 2011).

Bathke and Cassel (1991) also demonstrated the strong effect of macroporosity on the vertical and horizontal k_{sat}, yet highlighted the importance of getting the volume of the sample right in order to properly represent the existing pore arrangement that influences the measurements of directional water flow. Although Germer and Braun (2015) suggested that samples with volumes > 1 dm^3 are needed to capture the influence of macropores on the directional behavior of k_{sat}, our 579-cm^3 cores were sufficient to show differences in pore arrangement between sampling orientations for the studied soil.

The degree of anisotropy of k_{sat} was not affected by compaction or CC treatments (Table 2). Comparably, Wagger and Denton (1989) found that for vertical measurements in the topsoil, CC [hairy vetch (*Vicia villosa* Roth.)] effects on k_{sat} only existed in untrafficked but not in trafficked areas. More studies are needed on CC effects on physical properties, particularly k_{sat} in the subsoil, especially with regard to measuring the degree of anisotropy.

3.4 | Residual anisotropic behavior of the subsoil pore system

The results from Aarslev in 2017 were compared with those from samples taken in 2015. In the –CC plots in 2015

(Table 3), the compacted soil exhibited a negative effect on ρ_b, ε_a, and k_a for both the vertical and horizontal directions ($p < .05$). The ρ_b, ε_a, and k_a showed isotropic behavior, as similar values were obtained in the vertical and horizontal directions [e.g., the degree of anisotropy was equal to 1 ($p > .05$)]. The pore morphology indices in 2015 (i.e., PO1 and *R*-ratio) showed anisotropy in both the control and compacted soils ($p < .05$), except for PO1 in the control soil ($p = .08$). The k_{sat} value of the control was also anisotropic but k_{sat} values were similar in the vertical and horizontal direction for the compacted soil in 2015 at the Aarslev site.

In the same experiment in Flakkebjerg, Obour et al. (2017) reported that 1 yr after completing the compaction experiment (in 2014), samples of the same volume as in this study showed the direction-independent behavior of k_a for the control and compacted soils at 0.3 m depth, as well as no compaction effect on the degree of anisotropy. Additionally, they found that PO1 was strongly anisotropic for the control but not for the compacted soil at 0.3 m depth.

These results show that the general isotropic behavior of k_a in the subsoil at Aarslev in 2015 was still evident in our results from samples taken in 2017; in Flakkebjerg, the k_a in 2014 tended to change to anisotropic behavior in 2017 for the control soil. This may be related to the creation of more biopores by crop roots or earthworms with time. A stronger indicator of this anisotropic behavior was the PO1 index at both sites, revealing that the pore morphological indices are more sensitive for detecting anisotropy than k_a per se.

Soracco et al. (2015) showed that for a silty soil, the strongly anisotropic behavior of k_{sat} disappears after traffic and that this effect remains after 2 yr. In another study conducted on a silty loam, Peng and Horn (2008) found that the load-induced anisotropy of soil strength persists for over 10 yr in the subsoil. Their results also showed that vertical k_a and k_{sat} were larger than their corresponding horizontal measurements in the subsoil, as earthworm channels overrode the contribution of the platy structure to the horizontal porosity.

However, the anisotropic behavior of k_{sat} varied with time and soil depth according to the results found in a sandy loam soil by Petersen et al. (2008). In their study, k_{sat} was larger in the horizontal direction 1 mo after ploughing but was not direction-dependent after 8 or 32 mo in the transition layer at 0.25 m; this can be attributed to the settlement of the soil. They also showed strong anisotropic behavior with smaller k_{sat} values in the horizontal direction than in the vertical direction in the subsoil (0.40–0.60 m) when assessed 8 or 32 mo after tillage, which was directly related to the abundance of biopores (Petersen et al., 2008).

It is thus apparent that traffic events that induce subsoil compaction have effects that persist in the soil profile and contribute significantly to dynamic soil properties that affect the transport of air and water in the subsoil. This negative influence of soil compaction on subsoil properties could not, in

TABLE 3 Dry bulk density (ρ_b), air-filled porosity (ε_a), air permeability (k_a), pore geometry index (PO1), ratio of non-Darcian to Darcian air permeability (*R*), and saturated hydraulic conductivity (k_{sat}) from the Aarslev site 2 yr after completion of the compaction experiment

Treatment	ρ_b H[a]	ρ_b V	ρ_b *H/V*	ε_a H	ε_a V	ε_a *H/V*	k_a H	k_a V	k_a *H/V*	PO1 H	PO1 V	PO1 *H/V*	*R* H	*R* V	*R* *H/V*	k_{sat} H	k_{sat} V	k_{sat} *H/V*
	$Mg\ m^{-3}$			$m^3\ m^{-3}$			μm^2			μm^2						$cm\ d^{-1}$		
Control	1.73[b] a	1.74 a	0.99 a ns	0.11 b	0.11 b	1.00 a ns	18.4 b	17.6 b	1.05 a ns	68.2 b	150.4 b	0.45 a ns	0.90 a	0.76 a	1.20 a*	30.9 a	961.3 b	0.03 a*
Compacted	1.81 b	1.85 b	0.98 a ns	0.06 a	0.05 a	1.34 a ns	1.7 a	2.4 a	0.69 a ns	22.6 a	112.1 a	0.20 a*	1.01 b	0.86 b	1.17 a*	23.0 a	25.4 a	0.90 b ns

*Significantly different from 1. ns, not significantly different from 1.

[a]H, horizontal direction; V, vertical direction, *H/V*, degree of anisotropy.

[b]Values in a column followed by the same lowercase letters are not significantly different between treatments.

this study, be speedily reversed with fodder radish to levels of nonrestriction of the measured soil physical parameters for root growth and fluid flow (i.e., a decrease in bulk density and an increase in gas and water transport). Although our results showed a weak trend of increased gas and water flow in the compacted soil after 4 yr of including a fodder radish cover crop, conclusions as to the effects of fodder radish as a biosubsoiler and its influence on changes in the anisotropic behavior of the physical properties of the studied compacted subsoil cannot be drawn.

Our previous study in intact soil columns also demonstrated that fodder radish did not positively impact the pore network of the compacted subsoil in Aarslev; however, other species such as lucerne and chicory (*Cichorium intybus* L.) showed greater potential as biosubsoilers by creating a larger, more connected, and complex pore network in the compacted layer (Pulido-Moncada, Katuwal, Ren, Cornelis, & Munkholm, 2020a). Further studies involving different species with the potential to penetrate hard layers could provide better quantification of CC-induced changes in the anisotropy of soil physical parameters in compacted subsoils.

4 | CONCLUSION

The studied sandy loam subsoils displayed anisotropic behavior for convective gas (k_a, PO1) and water transport (k_{sat}), with larger values in the vertical than in the horizontal direction irrespective of compaction or CC treatment. For the *R*-ratio, larger values were found in the horizontal than in the vertical direction. Our results imply that tube-like vertical pores play a dominant role in subsoil gas and water flow for the studied sandy loam soils. The fodder radish CC showed a nonsignificant trend towards improved conditions for convective gas and water transport (i.e., higher k_a, PO1, k_{sat}, and larger degrees of anisotropy), suggesting the greater contribution of vertical biopores in the +CC than in the –CC plots. The CC plots had, on the other hand, no clear effect on bulk soil pore characteristics (bulk density) and air-filled porosity. Our study suggests that 4 yr of an autumn fodder radish cover crop in rotation with spring barley may tend to enhance convective gas and water transport properties but that the bulk soil characteristics remained relatively unchanged. Further studies are therefore needed to explore the long-term effects of a fodder radish cover crop on subsoil pore characteristics and soil functioning, as well as the use of different cover crop species that may have greater potential to function as biosubsoilers.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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ORCID

Mansonia Pulido-Moncada https://orcid.org/0000-0002-8920-8160
Pedro Paulo Gonçalves Zanini https://orcid.org/0000-0003-0126-211X
Lars J. Munkholm https://orcid.org/0000-0002-4506-9488

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