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Residual effects of compaction on the subsoil pore system—A functional perspective

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Abstract

Subsoil compaction caused by heavy traffic affects the soil pore system, resulting in long-term damage to soil functions. The study contrasted two treatments from compaction experiments conducted at three different sites in Denmark: non-trafficked control soil and soil subjected to four annual traffic events (2010–2013) with a wheel load of 58 to 78 kN. A cover crop of fodder radish (*Raphanus sativus* L.) was grown in half of the initial experimental plots after completion of the compaction treatments (2013 and onwards). In the spring of 2017, undisturbed soil cores were sampled at 0.3 and 0.5 m depth. The air-filled porosity (ε_a), air permeability (k_a) and gas diffusivity (D_s/D_o) were quantified for samples equilibrated to –100 hPa matric potential. Soil pore structural indicators were estimated from the combination of ε_a, k_a, and D_s/D_o. The ratio of non-Darcian to Darcian k_a (R) was also used as a pore morphology indicator. For all sites and depths, compaction reduced ε_a, D_s/D_o, $k_{a\text{-}Darcy}$, PO1 ($k_{a\text{-}Darcy}/\varepsilon_a$) and the effective radius ($[(8k_{a\text{-}Darcy})/D_s/D_o]^{0.5}$) compared to control soil ($p < 0.05$). The Buckingham-X variable relating D_s/D_o and ε_a tended to be smaller for compacted soil, significantly for one of the sites. Compacted soils were also characterised by a significantly smaller R-ratio at high levels of $k_{a\text{-}Darcy}$ (> 32 μm^2), but also by having a tendency for the R-ratio to decrease rapidly with increasing pore air velocity compared to the control. The results reflect a compaction-induced reduction in the number of marginal pores connected to large arterial pores, promoting a simple pore system formed by continuous vertical pores. The compaction effect was not affected by the cover crop. Neither natural recovery nor fodder radish-induced mitigation of soil compaction was evident for the studied soils.

1 | INTRODUCTION

Subsoil compaction caused by heavy traffic has been identified as a major problem in global agriculture (Soane & Van Ouwerkerk, 1994). The compaction-induced soil deformation has adverse effects on plant growth and crop yield (Arvidsson & Håkansson, 2014; Lipiec & Hatano, 2003) and consequently on ecosystem services including protection of the environment (Etana et al., 2013; Götze et al., 2016). The soil's

Abbreviations: D_s/D_o, relative gas diffusivity; $k_{a\text{-}5hPa}$, non-Darcian permeability; $k_{a\text{-}Darcy}$, Darcian permeability; PO1 ($k_{a\text{-}Darcy}/\varepsilon_a$) and PO2 ($k_{a\text{-}Darcy}/\varepsilon_a{}^{\wedge 2}$), pore geometry indices; r_{eff}, effective pore radius; *R-ratio, relation between the Darcian air permeability and the apparent air permeability at 5hPa pneumatic pressure (non-Darcian)*; *vpore, average pore air velocity*; X, Buckingham-model exponent; ε_a, volume of air-filled porosity; ρ_b, soil dry bulk density.

ability to mitigate, for instance, the undesirable preferential flow of pollutants in macropores is associated with the degree of damage caused to soil pore system by compaction (Kulli, Gysi, & Flühler, 2003).

Measurement of gas diffusion and convection (air permeability) in combination with the volume of air-filled pores has been used for decades to evaluate management effects on the soil pore system (e.g. Gradwell, 1960; Groenevelt, Kay, & Grant, 1984). Ball (1981) further combined diffusion and permeability to create useful indicators for soil pore structural features. These include the number of pores in a cross-sectional area, the tortuosity of pores, and the effective radius, r_{eff}, also quantified in this study. Although these structural indicators were validated for artificial pore systems (Ball, 1981; Schjønning, 2019), the soil pore system in natural conditions is complex and far from resembling a bundle of circular tubes. The soil pore system is built up of pores of different size and shape, some of which can be continuous and interconnected and some that are not (Arah & Ball, 1994). A conceptual model of soil pores from a functional perspective developed by Arah and Ball (1994) divided the soil pore volume into three categories, i) arterial, ii) marginal, and iii) remote pores. The arterial pores were considered the main pathway for air transport (diffusion as well as convection), while marginal pores were assumed to branch from the arterial pores into the soil matrix. Remote pores were the isolated pores that did not contribute to air transport.

In agricultural soils, the pore system arrangement differs between the tilled layer and the subsoil (Schjønning, Munkholm, Moldrup, & Jacobsen, 2002). Lamandé, Schjønning, Dal Ferro, and Morari (2020) showed that while the tilled topsoil may best be described as a random collection of aggregates with a sponge-like pore system, the subsoil is better described by the Arah and Ball (1994) conceptual model with vertical (bio)pores dominating the air transport pathway. In compacted subsoil layers, deformation of soil structure leads to the development of a direction-dependent behaviour of the pore system, i.e. to vertical tube-like pores (Dörner & Horn, 2009). Such pore system changes occur because of the reduction in the number of pores branching (marginal pores) from the vertical pores (arterial pores) by soil compression (Schjønning et al., 2013b). Heavy traffic impact may not necessarily cause blockage of stable vertical or arterial pores, but may still cause a reduction in diameter (Blackwell, Green, & Mason, 1990; Schäffer et al., 2008). The continuous vertical biopores in the subsoil are of major significance for the gas and water transport in compacted soils (Schjønning, Pulido-Moncada, Munkholm, & Iversen, 2019). Hence, the further discussion of the gas measurements in this study will concentrate on the arterial and marginal soil pores.

Compaction effects on the subsoil pore system have been reported to persist for more than a decade (Alakukku, 1996; Berisso et al., 2012). Natural compaction recovery in the subsoil is very slow in terms of changes in soil properties because of the low frequency and intensity of factors such as wetting/drying, freezing/thawing, biological activity, and tillage in deep layers (Håkansson & Reeder, 1994). Mechanical subsoiling is frequently used as a tool for alleviation of subsoil compaction. However, mechanical disturbance reduces soil strength and penetration resistance, and the effects are usually short lived, as loosened soil is prone to recompaction (Olesen & Munkholm, 2007). Biological subsoiling by actively growing plant roots with the potential to penetrate hard layers is an alternative strategy for compaction mitigation (Materechera, Dexter, & Alston, 1991). Cover crops with roots that can penetrate hard layers create biopores and root channels that increase the pore volume of the compacted layer (Bodner, Leitner, & Kaul, 2014). Continuous, vertical biopores created by cover crops from the upper soil layer to the subsoil may enhance oxygen diffusion, water infiltration, and solute transport, but also allow species with poor penetration capacity to reach the subsoil (Kautz, 2015).

Core Ideas

- Trafficked-induced effects on subsoil pore characteristics persist four years after compaction.
- For temperate sandy loam soils, compaction enhances the dominance of vertical, arterial biopores.
- Fodder radish did not alleviate heavy traffic induced severe subsoil compaction.

The present study focused on residual effects of compaction on soil pore system functionality. For this purpose, we use the Arah and Ball (1994) approach and the ratio of non-Darcian and Darcian air permeability (Schjønning et al., 2013b) as potential tools to reveal functional characteristics of the pore system of compacted subsoil. The objectives of this study are to quantify the residual compaction effect, and the cover crop-induced recovery of compaction effects on the subsoil pore system for three sandy loam soils. It was hypothesised that i) subsoil compaction is effectively persistent, ii) compaction in the subsoil will increase the characteristics of a pore system dominated by arterial (bio)pores, and iii) that a fodder radish cover crop will mitigate subsoil compaction.

2 | MATERIALS AND METHODS

2.1 | Study sites

The study was conducted at the experimental fields located in Aarslev (55° 18′ 18″ N lat., 10° 26′ 52″E long.), Flakkebjerg (55° 19′ 42″ N lat., 11° 24′ 28″E long.), and Taastrup (55° 40′ 43″ N lat., 12° 16′ 43″E long.), Denmark. Soils at the experimental fields are sandy loams that have been classified as Luvisols using the WRB classification system. The Aarslev field is homogeneous in terms of texture, while Flakkebjerg and Taastrup exhibit a noticeable textural variation with depth across the experimental fields. Please consult Schjønning, Lamandé, Munkholm, Lyngvig, and Nielsen (2016) for detailed description of soil texture.

2.2 | Experimental treatments

In the present study, the most contrasting compaction treatments from the experiments conducted in 2010 to 2013 were selected: control (no traffic), and compacted, which involved traffic with a tractor–trailer combination driven wheel-by-wheel with 78 kN (M8, Aarslev and Flakkebjerg) or 58 kN (M6, Taastrup) wheel loads and multiple wheel passes (4-5) in one traffic event. The compaction treatment represents realistic field operations with machinery typically used in slurry application. Tires used were all radial ply with tractor rear and trailer wheel widths 610 to 800 mm, and tire inflation pressures commonly used by local contractors (150–300 kPa). At all sites, the traffic experiment was conducted annually when the soils were near field capacity before seeding spring barley (*Hordeum vulgare* L.). Schjønning et al. (2016) provide a detailed description of the traffic experiments including details of tyres and wheel loads.

The experimental treatments were established in a randomised complete block design with four replicates. In August 2013, the main compacted replicates were split so that one-half had fodder radish (*Raphanus sativus* L.) sown as a cover crop, while the other half of the plot was left bare without a cover crop. After spring barley harvesting, fodder radish was sown every year from 2013 to 2016 in early August and incorporated into the soil by mouldboard ploughing in late autumn.

2.3 | Soil sampling

In spring 2017, three sampling points were selected in each of the split-plots, at each of which three minimally disturbed soil samples (100 cm^3) were taken at 0.30 and 0.50-m depth. A total of 144 samples per depth and site (four blocks × two treatments × two subplots × three sampling spots × three replicate cores) was collected. Soil cores were kept at 2 °C until laboratory analyses were conducted.

[Correction added on May 29, 2020 after first online publication: in the sentence "Soils at the experimental fields are sandy loams that have been classified as Luvisols using the FAO classification system." FAO has been replaced with WRB].

2.4 | Laboratory analyses and calculations

The soil cores were first saturated by capillarity on tension tables and then drained at –100 hPa matric potential. First, air permeability ($k_{a\text{-}Darcy}$, Darcian permeability) was measured using the Forchheimer approach at four pneumatic pressures (Schjønning & Koppelgaard, 2017), including estimation of the apparent permeability at 5 hPa pneumatic pressure across the soil core ($k_{a\text{-}5hPa}$, non-Darcian permeability). Then, the volume of air-filled porosity (ε_a) was measured for the Taastrup site by using an air pycnometer (Flint & Flint, 2002; Rüegg, 2000), but calculated as the difference between the total pore volume and the volume of water retained at –100 hPa matric potential for the Aarslev and Flakkebjerg sites.

Subsequently, the relative gas diffusivity (D_s/D_o) was calculated from measurements conducted using the one-chamber, one-gas method described by Schjønning, Eden, Moldrup, and de Jonge (2013a). Afterwards, soil cores were oven-dried at 105 °C for estimation of soil dry bulk density (ρ_b) and total pore volume (assuming a particle density of 2.65 Mg m^{-3}).

The pore geometry indices, PO1 (Eq. [1]) and PO2 (Eq. [2]), were derived from $k_{a\text{-}Darcy}$ and $\varepsilon_{a,}$ as suggested by Groenevelt et al. (1984). Additionally, the Buckingham-*X* parameter (Eq. [3]) (Buckingham, 1904), the effective pore radius (r_{eff}) (Eq. [4]) derived from the tube model proposed by Ball (1981), and the *R*-ratio of Non-Darcian to Darcian Air Permeability (Eq. [5]) (Schjønning et al., 2013b) were also calculated for each individual sample.

$$PO1 = \frac{k_{a-\text{Darcy}}}{\varepsilon_a} \tag{1}$$

$$PO2 = \frac{k_{a-\text{Darcy}}}{\varepsilon_a{}^2} \tag{2}$$

$$X = \frac{\log(D_s/D_o)}{\log\left(\varepsilon_a\right)} \tag{3}$$

$$r_{\text{eff}} = \sqrt{\frac{8 \times k_{a-\text{Darcy}}}{D_s/D_o}} \tag{4}$$

$$R = \frac{k_{a-5hPa}}{k_{a-\text{Darcy}}} \tag{5}$$

[Correction added on May 29, 2020 after first online publication: in the sentence "Additionally, the Buckingham-X parameter (Eq. (3)) (Buckingham, 1904), the effective pore radius (Eq. (4)) derived from the tube model proposed by Ball (1981), and the *R*-ratio of Non-Darcian to Darcian Air Permeability (Eq. (5)) (Schjønning et al., 2013b) were also calculated for each individual sample." (r_{eff}) is inserted after radius].

TABLE 1 Mean value of soil properties from three sandy loam soils four years after completion of compaction experiment with heavy machinery

Depth[a] m	Compaction[c]	ρ_b Mg m^{-3}	ε_a[b] m^3 m^{-3}	D_s/D_o	Buckingham-X [log(D_s/D_o)/logε_a]	$k_{a\text{-Darcy}}$ µm^2	PO1 $k_{a\text{-Darcy}}/\varepsilon_a$	PO2 $k_{a\text{-Darcy}}/\varepsilon_a^2$	r_{eff} µm
Aarslev[d]									
0.3	Control	1.68a	0.12b	0.0078b	2.23b	9.6b	89a	816a	99a
	Compacted	1.80b	0.07a	0.0032a	2.00a	2.4a	52a	1003a	78a
0.5	Control	1.62a	0.14b	0.0130b	2.14a	28.7b	221b	1700a	133b
	Compacted	1.70b	0.09a	0.0054a	2.07a	7.0a	91a	1176a	102a
Flakkebjerg[d]									
0.3	Control	1.67a	0.12b	0.0074b	2.20a	19.2b	189b	1859a	145b
	Compacted	1.75b	0.09a	0.0031a	2.14a	4.3a	78a	1215a	105a
0.5	Control	1.62a	0.16b	0.0168b	2.12a	35.4b	249b	1751a	130a
	Compacted	1.72b	0.10a	0.0066a	2.07a	11.6a	136a	1587a	119a
Taastrup[d]									
0.3	Control	1.62a	0.10b	0.0084b	1.99a	33.3b	383b	4411a	178b
	Compacted	1.77b	0.06a	0.0034a	1.97a	9.1a	169a	3128a	146a
0.5	Control	1.60a	0.15b	0.0158b	2.12a	95.0b	679a	4858a	219a
	Compacted	1.65b	0.11a	0.0105a	2.04a	53.5a	502a	4949a	201a
Across-location									
0.3	Control	1.66a	0.11b	0.0078b	2.14b	18.3b	186b	1885a	137b
	Compacted	1.77b	0.07a	0.0033a	2.03a	4.8a	94a	1731a	109a
0.5	Control	1.61a	0.15b	0.0151b	2.13b	45.9b	334b	2437a	156b
	Compacted	1.69b	0.10a	0.0072a	2.06a	16.4a	184a	2065a	135a

[a] ρ_b, bulk density; ε_a, air-filled porosity; D_s/D_o, relative diffusivity where D_s and D_o are the diffusion coefficients in soil and air, respectively; *Buckingham-X*, indicator of connectivity and tortuosity of soil pores; $k_{a\text{-Darcy}}$, Darcian air permeability; PO, pore geometry indices (µm^2). r_{eff}, effective pore radius, $[(8k_{a\text{-Darcy}})/D_s/D_o]^{0.5}$.
[b] ε_a, D_s/D_o and $k_{a\text{-Darcy}}$ measured when soil samples have been drained to a matric potential of –100 hPa.
[c] Control undergoes no compaction treatment, and compacted soil undergoes heavy traffic (wheel loads of 78 kN for Aarslev and Flakkebjerg and 58 kN for Taastrup) with multiple passes (4-5).
[d] Values in a column followed by the same letter are not significantly different among treatments in the same depth ($p = 0.05$).

2.5 | Statistical analyses

A mixed model with compaction treatment and cover crop effect, as fixed effects and block as well as compaction treatment × block × cover crop interaction as random effects was used to evaluate compaction and cover crop effects on pore characteristics and bulk density. The sampling spot effect nested within the experimental plot (compaction treatment × block × cover crop) was also treated as a random effect in the model. Compaction and cover crop effects across locations were also tested, treating location as a random effect (assuming the three locations randomly represent sandy loam soils deriving from morainic till). The statistical analyses referred above were performed using the statistical package SPSS (version 24, SPSS Inc.). All tests were conducted using the 5% level of significance. The analysis of the relationship between the *R*-ratio and the air velocity were performed by adjusting a nonlinear regression for estimating the curve defined in the equation (7), as suggested by Schjønning et al. (2013b) using the function nls of the R package nlme (R Core Team, 2017). Tests to the parameter *b* in the nonlinear regression were done by nonparametric bootstrap (with 10,000 bootstrap replicates).

[Correction added on May 29, 2020 after first online publication: in the table footnote below Table 1 “PO, pore organisation indices” is replaced with “PO, pore geometry indices (µm^2)”].

3 | RESULTS AND DISCUSSION

3.1 | Persistency of subsoil compaction effects

Results for the soil bulk density (ρ_b), pore volume, and pore geometry are given for each site and depth and averaged across compaction treatment and cover crop in Table 1 and 2, respectively. There was no significant interaction effect between the experimental factors of compaction × cover crop, except for D_s/D_o ($p < 0.029$) at 0.5-m depth for the Taastrup site (Supplemental Table S1). At the Aarslev site, nonsignificant trends

TABLE 2 Mean value of soil properties for three sandy loam soils after four years of fodder radish used as cover crop (CC) for subsoil compaction mitigation.[a]

Depth m	Cover crop[c]	ρ_b Mg m^{-3}	ε_a[b] m^3 m^{-3}	D_s/D_o	Buckingham X [$\log(D_s/D_o)/\log\varepsilon_a$]	$k_{a\text{-Darcy}}$ µm^2	PO1 $k_{a\text{-Darcy}}/\varepsilon_a$	PO2 $k_{a\text{-Darcy}}/\varepsilon_a^2$	r_{eff} µm
Aarslev									
0.3	+CC	1.76a	0.09a	0.0048a	2.07a	4.7a	71a	994a	88a
	–CC	1.72a	0.11a	0.0051a	2.17a	5.0a	66a	823a	88a
0.5	+CC	1.66a	0.10a	0.0079a	2.06a	15.5a	166a	1792a	125a
	–CC	1.66a	0.12a	0.0089a	2.15a	13.0a	121a	1116a	108a
Flakkebjerg									
0.3	+CC	1.71a	0.11a	0.0051a	2.14a	11.7a	166a	1859a	136a
	–CC	1.71a	0.10a	0.0045a	2.20a	7.0a	89a	1214a	112a
0.5	+CC	1.67a	0.13a	0.0109a	2.08a	22.4a	203a	1851a	128a
	–CC	1.67a	0.13a	0.0102a	2.11a	18.5a	167a	1502a	121a
Taastrup									
0.3	+CC	1.70a	0.08a	0.0048a	2.03a	16.3a	230a	3250a	165a
	–CC	1.70a	0.08a	0.0060a	1.93a	18.6a	281a	4246a	158a
0.5	+CC	1.63a	0.13a	0.0128a	2.08a	75.3a	619a	5332a	217a
	–CC	1.63a	0.13a	0.0131a	2.08a	67.5a	552a	4508a	203a
Across locations									
0.3	+CC	1.72a	0.09a	0.0049a	2.08a	9.7a	140a	1925a	126a
	–CC	1.71a	0.10a	0.0052a	2.10a	9.2a	125a	1695a	118a
0.5	+CC	1.65a	0.12a	0.0103a	2.07a	29.6a	276a	2563b	151a
	–CC	1.65a	0.13a	0.0106a	2.11a	25.3a	223a	1963a	138a

[a] ρ_b, bulk density; ε_a, air-filled porosity; D_s/D_o, relative diffusivity, where D_s and D_o are the diffusion coefficients in soil and air, respectively; *Buckingham X*, indicator of connectivity and tortuosity of soil pores; $k_{a\text{-}Darcy}$, Darcian air permeability; PO, pore geometry indices (µm^2); r_{eff} = effective pore radius; $[(8k_{a\text{-}Darcy})/D_s/D_o]^{0.5}$.
[b] ε_a, D_s/D_o and $k_{a\text{-}Darcy}$ measured when soil samples have been drained to a matric potential of –100 hPa.
[c] +CC and –CC represent the subplots with and without fodder radish as a cover crop, respectively
Values in a column followed by the same letter are not significantly different among treatments in the same depth (p = 0.05).

for compaction × cover crop interaction were observed for ε_a ($p = 0.085$) at 0.3-m depth, and for $k_{a\text{-}Darcy}$ ($p = 0.106$), PO1 ($p = 0.076$) and r_{eff} ($p = 0.073$) at 0.5-m depth. However, the cross-location analysis did not show a significant interaction effect of compaction × cover crop for any of the parameters under study. Therefore, compaction and cover crop effects are discussed separately in the following.

Four years after the completion of repeated annual heavy traffic on the studied sandy loam soils, the compaction-related detrimental impact on soil bulk density and pore system at 0.3-m depth reported by Schjønning, Lamandé, Crétin, and Nielsen (2017) still persists. At all three sites under study, compacted soils also exhibited a significant increment in ρ_b at 0.5-m depth compared to the control soil ($p < 0.05$) (Table 1). Compaction reduced ε_a to 58 to 75% and 63 to 73% of the control soil at 0.3-m and 0.5-m depth, respectively. The ε_a values were below the minimum threshold for adequate aeration of 0.10 m^3 m^{-3} (Grable & Siemer, 1968), except for Taastrup (0.11 m^3 m^{-3}) at 0.5-m depth.

Previous studies from the same experiment showed that aeration limitation was reached during experimentation at the three sites under study. At Aarslev, after three years of experimentation (in 2012), compaction reduced ε_a to 51% of the control in the 0.3-m layer whereas no significant reduction of ε_a was estimated for Flakkebjerg and Taastrup after two years of experimentation (in 2011) (Schjønning et al., 2017).

However, at Flakkebjerg, in 2014, after four years of the heavy traffic experiments, reduction of ε_a caused by compaction was estimated to be 44% of the control at 0.3-m depth, and 69% at 0.5-m depth (Obour, Schjønning, Peng, & Munkholm, 2017). Samples taken in 2017 from Flakkebjerg show that the ε_a of the compacted soil was 75% of the control (Table 1), which reflects a degree of recovery on this parameter. For the Aarslev site, two years after the completion of the experiment (in 2015), ε_a had dropped to 59 and 61% of the control at 0.3- and 0.5-m depth, respectively (Pulido-Moncada, Munkholm, & Schjønning, 2019). For Aarslev there was no recovery of ε_a from 2015 to 2017. The previous studies and our present results suggest that for the Flakkebjerg and Taastrup soils, heavy traffic does not cause detectable damage to soil porosity during the first two years, but made the soil vulnerable to the subsequent compaction events. For Aarslev, an experimental period of three years was sufficient to reach a significant reduction of soil air-filled porosity.

Results show that at 0.3 m depth, the D_s/D_o was 40 to 42% smaller in the compacted soil than in the control. The measured values of D_s/D_o were < 0.005 in the compacted soil, indicating a high risk of anoxic conditions at –100 hPa matric potential at all sites (Stepniewski, 1981). Although a significant reduction of D_s/D_o was also found at 0.5-m depth (39-66% of the control), the values remain within the threshold range from 0.005 to 0.02 (Stepniewski, 1981), with Aarslev and Flakkebjerg close to the minimum critical limit. Our previous study at Aarslev, two years after the final compaction treatment, also showed D_s/D_o -values < 0.005 at both 0.3- and 0.5-m depth (Pulido-Moncada et al., 2019). The D_s/D_o had dropped from 52 and 61% of the control in 2015 to 41 and 42% in 2017, at 0.3- and 0.5-m depth, respectively. This indicates, in similarity to ε_a, a slight natural recovery for the Aarslev soil.

The compaction treatment induced reduction in the volume of large pores, as mentioned above, was also reflected in low Darcian permeabilities, $k_{a\text{-}Darcy}$ ($p < 0.05$) (Table 1). The $k_{a\text{-}Darcy}$ values range from 2.4 to 9.1 μm^2 for the compacted soil at 0.3-m depth (22 to 27% of the control), which is lower than the critical limit of 20 μm^2 proposed by Fish and Koppi (1994). Limited or low permeability persisted down to 0.5-m depth only for Aarslev and Flakkebjerg. The significant reduction in $k_{a\text{-}Darcy}$ by compaction for the three sites is in line with previous measurements in the same field trials after two to three years of experimentation (all three sites; Schjønning et al., 2017), one year after completion (Flakkebjerg; Obour et al., 2017) and two years after completion of the experiment (Aarslev; Pulido-Moncada et al., 2019). Note that the Forchheimer methodology (Schjønning & Koppelgaard, 2017) was used for estimating Darcian flow in this study and in the study by Pulido-Moncada et al. (2019), whereas results presented in Obour et al. (2017) and Schjønning et al. (2017) are non-Darcian permeability, $k_{a\text{-}5hPa}$.

Persistency of subsoil compaction effect on soil physical properties has been previously reported under different soil and climate conditions (Arvidsson & Håkansson, 2014; Berisso et al., 2013; Håkansson & Reeder, 1994).

3.2 | Compaction effects on subsoil pore characteristics

Soil gas diffusivity, D_s/D_o, increased exponentially with the increase in ε_a, (Figure 1), following the Buckingham model ($D_s/D_o = \varepsilon_a{}^X$). In Figure 1, the curved lines show the Buckingham relation for the mean values of X (Table 1) for the control and the compacted soil. In addition, we inserted a line for $X = 1$, representing straight tubes running parallel to the diffusion direction. A study conducted by Schjønning et al. (2013b) on autoclaved aerated concrete samples suggests that an isotropic sponge-like condition can be represented by the Buckingham relation at $X = 8$. Our data for the sandy loam subsoils fall in between these two extremes (range 1.97-2.23, Table 1). An X-value of 1.39 was found for a clay subsoil in Finland, and heavy compaction decreased X to 1.15 (Schjønning et al., 2013b). Our experimental subsoils thus tend to be far from an isotropic sponge but less 'tube-like' than the clayey subsoil from Finland.

The Buckingham-X parameter is inversely related to the tortuosity parameter established by Ball (1981), as elaborated by Schjønning et al. (2013b). Arah and Ball (1994) found that diffusion constraints interpreted, as tortuosity of the diffusion pathway cannot be distinguished from the effects of marginal pores branching from the main diffusion pathway. They chose to abandon the concept of tortuosity and explain their results instead by the concept of arterial and marginal pores. The fact that in the present study all combinations of location and depth displayed the same tendency of traffic-induced lower X-values (significantly for Aarslev at 0.3-m with p-value < 0.05; and across all locations at 0.3-m and 0.5-m with $p \leq 0.01$, Table 1), indicates that compaction enhanced the influence of vertical, arterial (bio)pores relative to that of the marginal pores. This may also be taken as an indication that the marginal pores branching from the arterial pores were either diminished in size or closed by the compaction process.

Schjønning (1989) and Martínez et al. (2016) compared the long-term effects of different tillage systems. For the upper subsoil layer (respectively 0.25 and 0.4-m depth), they found a D_s/D_o - ε_a relation that would give higher Buckingham-X values for mouldboard ploughed soil compared to soil experiencing shallow or no-till systems (Figure 3 of the Schjønning (1989) paper and Figure 4 of the Martínez et al. (2016) paper). Assuming that repeated mouldboard ploughing densifies the soil below ploughing depth, these observations are at odds with the results obtained in this study, where compaction has been inflicted experimentally with heavy traffic. The deviating trends may be due to tortuosities related to differences in horizontal stresses for the traffic inflicted. We encourage more studies to further illuminate this aspect.

The relationship between the magnitude of $k_{a\text{-}Darcy}$ and the magnitude of ε_a was assessed from the PO1 and PO2 indices. Our results show that compaction affected PO1

[Correction added on May 29, 2020 after first online publication: in the sentence "For the upper subsoil layer (0.25 respectively 0.4-m depth), they found a D_s/D_o - ε_a relation that would give higher Buckingham-X values for mouldboard ploughed soil compared to soil experiencing shallow or no-till systems (Figure 3 of the Schjønning (1989) paper and Figure 4 of the Martínez et al. (2016) paper)." (0.25 respectively 0.4-m depth) has been replaced with (respectively 0.25 and 0.4-m depth)].

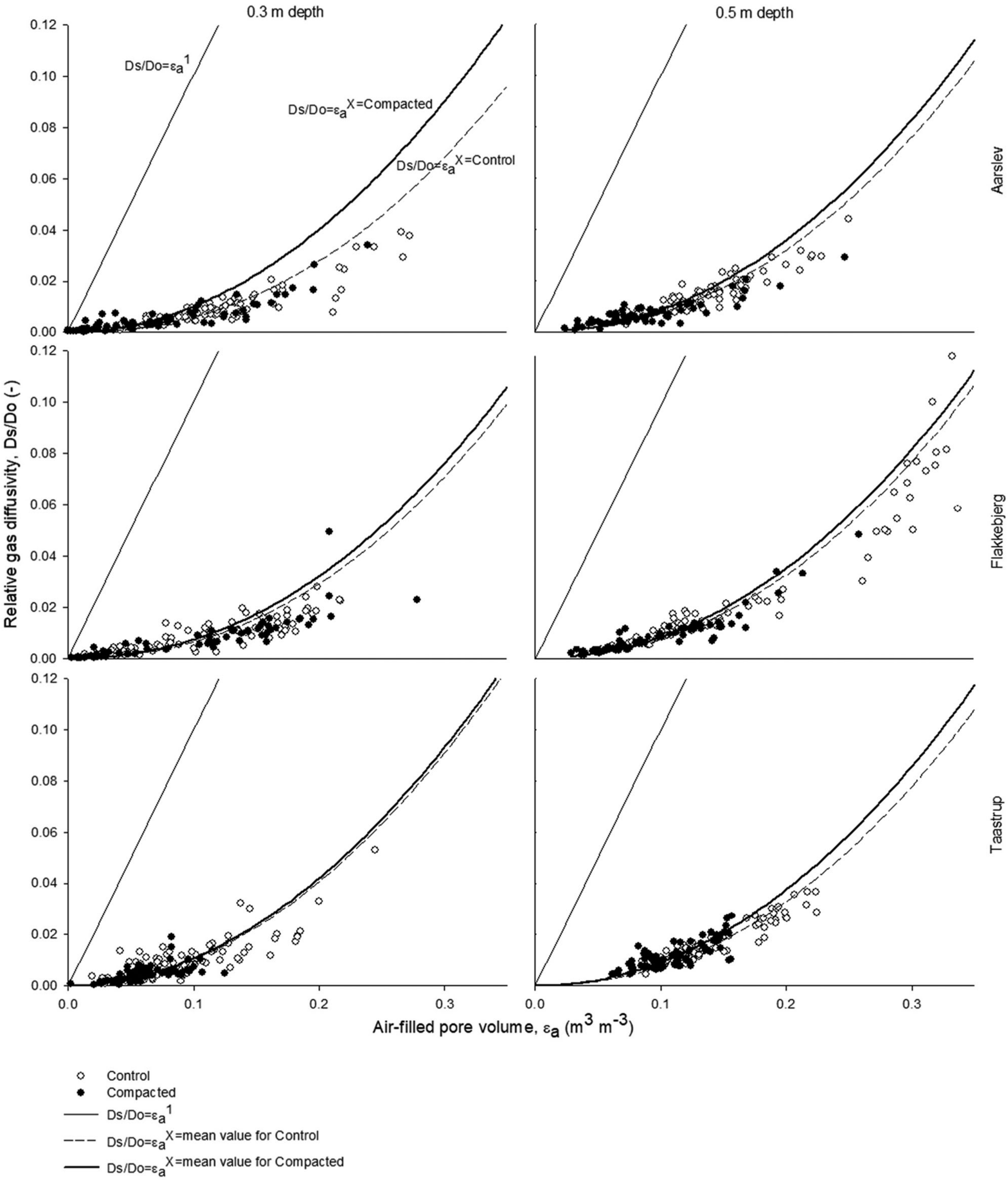

FIGURE 1 Relative gas diffusivity related to air-filled porosity at –100 hPa matric potential, for three sandy loam soils. Data points fitted by the Buckingam model for $X = 1$ (fine solid lines) and X = mean value of X for the control (dash lines) and for compacted soil (coarse solid lines). Control undergoes no compaction treatment, and compacted soil undergoes heavy traffic with multiple passes (4-5)

($p < 0.05$, Table 1), except for Aarslev at 0.3-m depth and Taastrup at 0.5-m depth where the p-values were 0.10 and 0.11, respectively. However, across locations compaction significantly reduced the PO1 index to 51% and 55% of the control at 0.3 m ($p = 0.001$) and 0.5 m ($p < 0.001$), respectively.

Pore geometry index 1 has also been labelled the specific permeability (Schjønning et al., 2013b) as it normalizes the permeability to a unit value of the air-filled pore volume available for convective transport. Given the lower PO1 values for the compacted than for the control soil, we realize that soil pore characteristics other than ε_a are governing the observed differences in k_a. According to Poiseuille's law, smaller pores will reduce k_a. This effect is accounted for by the PO2 index (Groenevelt et al., 1984), which does not differ for the control and compacted soil ($p > 0.05$, Table 1). The trends in PO1 and PO2 therefore reveal that compaction has reduced the air-filled pore volume as well as the size of the pores active in transport.

Following the knowledge gained from PO1 and PO2, Table 1 shows that the r_{eff} was significantly reduced by compaction in Flakkebjerg and Taastrup sites at 0.3-m depth, in Aarslev at 0.5-m depth, and across-location at both depths ($p = 0.010$). Therefore, the reduction in $k_{a\text{-}Darcy}$ after compaction induced by heavy wheel loads might be attributable both to the smaller pore volume (ε_a) and to the decrease in pore radius (r_{eff}). Our previously reported results from this field experiment at Aarslev showed a non-significant trend in the reduction of pore radius by compaction (Pulido-Moncada et al., 2019).

3.3 | Pore morphology effects on pore fluid flow

Figure 2 displays the relation between Darcian air permeability and apparent air permeability at 5 hPa pneumatic pressure (non-Darcian). For each combination of soil depth and site, $k_{a\text{-}Darcy}$ was larger than $k_{a\text{-}5hPa}$, and this deviation increased with increasing level of permeability. This result corresponds with those from a previous study for the Aarslev site in the same experiment (Schjønning et al., 2019). Partitioning of the data was conducted to further evaluate the compaction effect on the R-ratio for different levels of air permeability, that is, $k_{a\text{-}Darcy} < 3.2\ \mu\text{m}^2$, 3.2-32 μm^2, and $> 32\ \mu\text{m}^2$. It is remarkable, but in accordance with our previous study, that the R-ratio ($k_{a\text{-}5hPa}$ relative to $k_{a\text{-}Darcy}$) at high levels of permeability was very low.

For the control soil in this study the range was from 0.32-0.56, at $k_{a\text{-}Darcy} > 32\ \mu\text{m}^2$, depending on site and soil depth (Table 3). Compaction significantly reduced the R-ratio at the high-level of $k_{a\text{-}Darcy}$ ($> 32\ \mu\text{m}^2$) for Aarslev at both 0.3- and 0.5-m depth, and at 0.3 m for the Taastrup site (Table 3). A similar, though nonsignificant trend was observed for Flakkebjerg ($p = 0.15$) and Taastrup ($p = 0.08$) at 0.5-m depth.

[Correction added on May 29, 2020 after first online publication: the sentence "Given the lower PO1 values for the control than for the compacted soil, we realize that soil pore characteristics other than ε_a are governing the observed differences in k_a." has been modified as "Given the lower PO1 values for the compacted than for the control soil, we realize that soil pore characteristics other than ε_a are governing the observed differences in k_a."].

The air-filled pore volume, ε_a, available for the gas transport explained the variation in the R-ratio poorly (analyses not shown). We, therefore, calculated the average pore air velocity (v_{pore}) at 5 hPa pneumatic pressure from the superficial air velocity at that pressure ($v_{\text{sup-5hPa}}$), and the fraction of ε_a.

$$v_{\text{pore}} = \frac{v_{\text{sup}-5hPa}}{\varepsilon_a} \tag{6}$$

Figure 3 shows that v_{pore} is a significant descriptor of R. For all six combinations of soil depth and site, the non-Darcian permeability relative to the Darcian air permeability (R-ratio) decreases with an increase in the pore air velocity. The relationship between the R-ratio and air velocity of the studied soils was well described following the exponential model suggested by Schjønning et al. (2013b).

$$R = R_0 + a \times \exp\left(-b \times v_{\text{pore}}\right) \tag{7}$$

where $R = k_{a\text{-}5hPa}/k_{a\text{-}Darcy}$, R_0 is an estimate of the equilibrium minimum R at an infinite v_{pore}, and a and b are coefficients determining the course of reduction from $R = 1$ to $R = R_0$.

None of the coefficients to Eq. (7) were significantly different between treatments ($p > 0.05$) (Table 4). However, we observed some general trends for the b-coefficient, relating to the rate at which R decreases with increases in v_{pore}. The higher the b-values, the more pronounced is the rate of decrease. For all combinations of site and soil depth, the b-coefficient was found to be higher for compacted than for the control soil (p-values ranging from 0.12 to 0.54). Although the difference was far from significant for each specific combination of location and depth, across-site average b-values for the 0.3-m depth control and compacted soil were 9.3 and 11.5, respectively. The same figures for 0.5-m depth were 3.9 and 7.2, that is, close to a compaction-induced doubling of b. Averaged across all three sites and both experimental treatments, b was 10.4 at 0.3-m depth, while it was nearly half that, $b = 5.6$, at 0.5 m depth (Table 4). We interpret these trends as follows. All agricultural soils in modern, mechanized agriculture exhibit a compacted plough pan (e.g., Barraclough & Leigh, 1984; Munkholm, Schjønning, Jørgensen, & Thorup-Kristensen, 2005; Schneider & Don, 2019). For this upper subsoil layer, the pore system is dominated by vertical biopores with a dense soil matrix between these pores (e.g. Blackwell et al., 1990). In other words, the pore system may be well described by the Arah and Ball (1994) conceptual model of arterial and marginal pores. Now, we hypothesize that this pattern is more pronounced for the plough pan layer (0.3 m) than the deeper soil. We found higher b-values for the 0.3-m than the 0.5-m layer (Table 4). The estimate of pore air velocity, v_{pore}, is an average that does not take into

[Correction added on May 29, 2020 after first online publication: equations 6 and 7 have been updated].

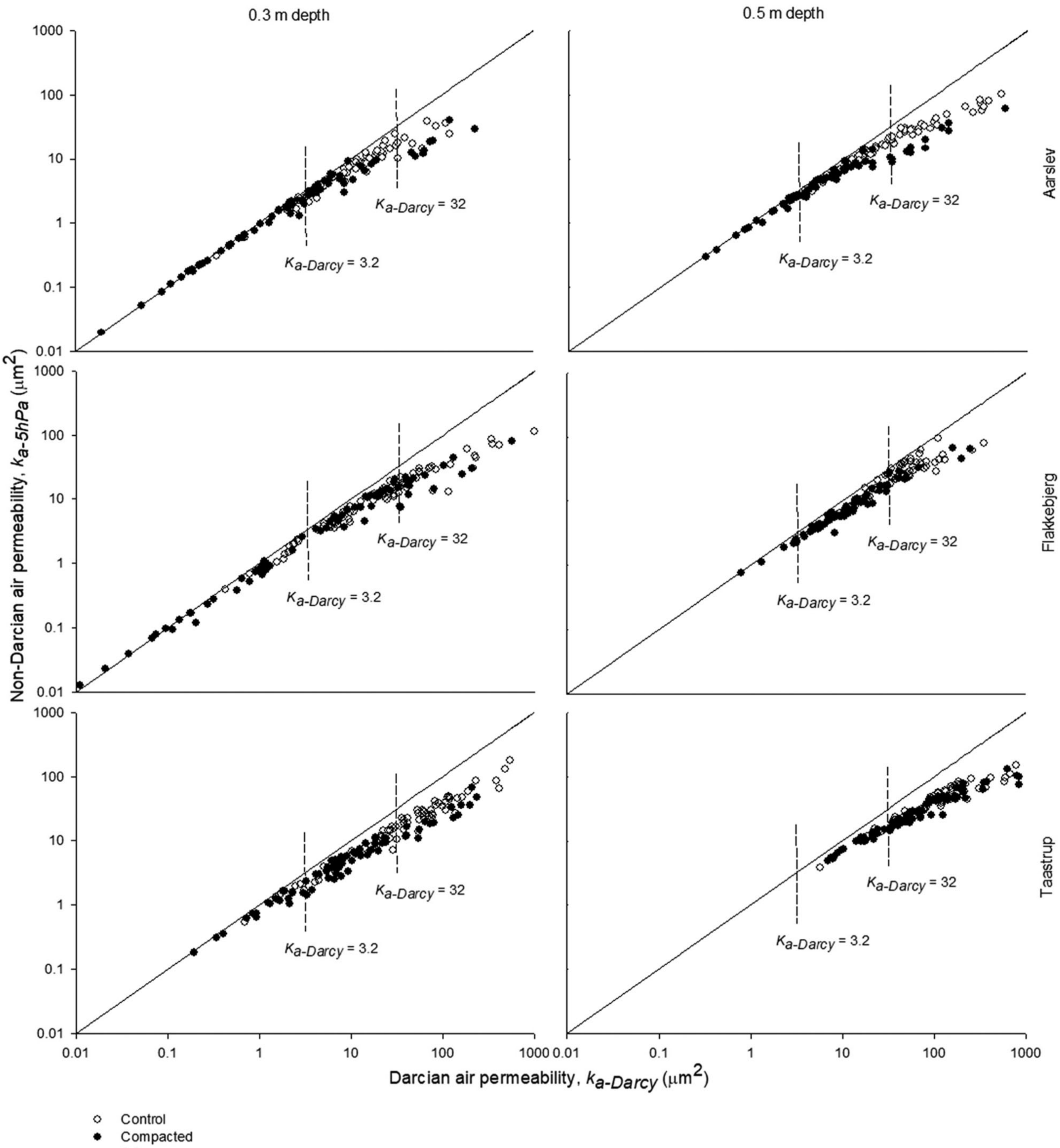

FIGURE 2 Estimates of the non-Darcian air permeability ($k_{a\text{-}5hPa}$) in relation to Darcian air permeability ($k_{a\text{-}Darcy}$). Control undergoes no compaction treatment, and compacted soil undergoes heavy traffic with multiple passes (4-5)

account differences in the pore size distribution. Where a large fraction of ε_a is taken up by vertical biopores (at 0.3-m compared with 0.5-m depth), the real v_{pore} in these pores is deemed to be higher than the average. In such cases, turbulent flow will be more dominant than where the soil flow is to a higher degree distributed to a more sponge-like air-filled pore system. The increase in *b* for compacted compared with the control soil at both soil depths (Table 4) is accordingly interpreted as a greater dominance of vertical biopores in the flow process. The trends discussed above are supported by our previous study at the Aarslev site for soil drained to -30 as well as –100 hPa (Schjønning et al., 2019). We consider the relation between the *R*-ratio and v_{pore} to be a promising tool for understanding the management effects on soil pores and their functionality. Nevertheless, our observations and interpretations need to be evaluated in future studies.

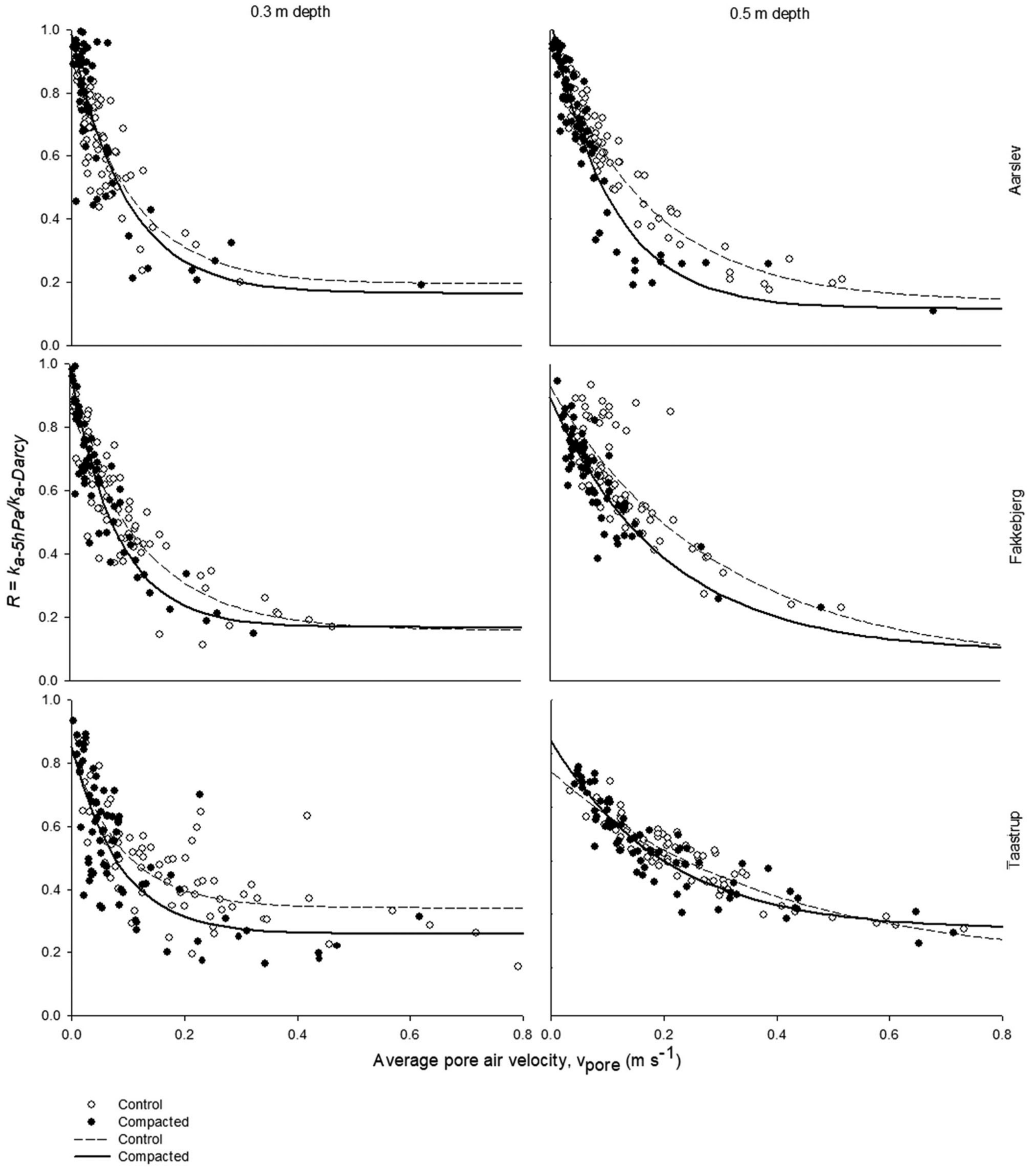

FIGURE 3 The ratio of non-Darcian and Darcian air permeability ($R = k_{a\text{-}5hPa}/k_{a\text{-}Darcy}$) to average pore air velocity at –100 hPa matric potential for three sandy loam soils. Control undergoes no compaction treatment, and compacted soil undergoes heavy traffic with multiple passes (4-5)

3.4 | Cover crop effect of subsoil pore characteristics

Our hypothesis on cover crop induced soil structure recovery was not confirmed as there was no significant effect of cover crop for any of the evaluated parameters (Tables 2 and S1). At the Aarslev site, the use of cover crop showed a nonsignificant trend for Buckingham-*X* ($p = 0.06$) and PO2 ($p = 0.07$) to be highest at 0.5-m depth. At Flakkebjerg there were weak trends ($p = 0.12$ to 0.17) for PO1, PO2 and r_{eff} to be highest for

TABLE 3 Values of the ratio of non-Darcian to Darcian air permeability ($R = k_{a\text{-}5hPa}/k_{a\text{-}Darcy}$) and the probability that it is different from unity within each compaction treatment and specific range in $k_{a\text{-}Darcy}$ when soil is drained to –100 hPa. The probability of $R_{Control}$ deviating from $R_{Compacted}$ is also shown

	Depth	$k_{a\text{-}Darcy}$ -range	Compaction				
			Control		Compacted		
Location	m	µm^2	R	$p(R <> 1)$[a]	R	$p(R <> 1)$	$p(R_{Control} <> R_{Compacted})$ [a]
Aarslev	0.3	<3.2	0.83	****	0.86	****	ns
		3.2-32	0.66	****	0.67	****	ns
		>32	0.37	****	0.22	****	**
	0.5	<3.2	–[b]	****	0.88	****	–[b]
		3.2-32	0.70	****	0.69	****	ns
		>32	0.40	****	0.26	****	**
Flakkebjerg	0.3	<3.2	0.80	****	0.85	***	ns
		3.2-32	0.60	****	0.63	****	ns
		>32	0.32	****	0.27	****	ns
	0.5	<3.2	–[b]		0.82	**	–[b]
		3.2-32	0.68	****	0.65	****	ns
		>32	0.56	****	0.45	***	ns (p = 0.15)
Taastrup	0.3	<3.2	0.74	**	0.75	****	ns
		3.2-32	0.54	****	0.53	****	ns
		>32	0.37	****	0.24	****	**
	0.5	<3.2	–[b]		–[b]		–[b]
		3.2-32	0.62	****	0.63	****	ns
		>32	0.38	****	0.33	****	ns ($p = 0.08$)

*$p \leq 0.05$
**$p \leq 0.01$
***$p \leq 0.001$.
****$p \leq 0.0001$
[a]ns; $p > 0.05$ (not significant).
[b]None or too few data.

TABLE 4 The b-coefficient of least squares fit to the relationship between R-ratio and air velocity of the studied soils, Eq. (7)

		Compaction			
Depth, m	Location	Control	Comp-acted	p-value[a]	Average, depths
0.3	Aarslev	9.1	10.3	0.28	10.4
	Flakkebjerg	7.8	12.2	0.49	
	Taastrup	11.1	11.9	0.12	
0.5	Aarslev	5.7	9.4	0.54	5.6
	Flakkebjerg	3.4	6.8	0.46	
	Taastrup	2.6	5.4	0.45	
Average, Compaction		6.6	9.3		

[a]p-values deriving from the regression including all soil cores for each combination of location and depth (see Figure 3).

plots with cover crop at 0.3-m depth, and at Taastrup there was a trend ($p = 0.08$) for Buckingham-X to be higher for cover crop at 0.3-m depth. The cover crop effect across-locations was only significant for PO2 at 0.5-m depth ($p = 0.039$) (with cover crop > without cover crop). A nonsignificant positive effect of the cover crop was seen for PO1 ($p = 0.092$) and r_{eff} ($p = 0.103$) at 0.5-m depth across-locations.

The tendency for conditions to improve for plots with cover crop in terms of higher PO1, PO2 and r_{eff} at 0.5-m depth, may indicate the formation of continuous biopores. However, the lack of a significant cover crop effect is in agreement with Welch, Behnke, Davis, Masiunas, and Villamil (2016), who found no compaction alleviation after three years of fodder radish in compacted headlands in organic systems in Illinois. These authors suggested that the short season available for growing a cover crop is a limiting factor for any short- or long-term cover crop effect on soil properties (Welch et al., 2016). This is also the case in Denmark, and may be one of the reasons for the poor performance of fodder radish in mitigating subsoil compaction in our experiment.

In contrast, other studies have shown that fodder radish has potential as a bio-subsoiler for soil compaction mitigation. Chen and Weil (2011) found a positive effect of two years of fodder radish on root counts of summer crops on highly compacted ($\rho_b > 1.70$ Mg m^{-3}) loam and loamy sand soils in Maryland. This was linked to an increase in the number of biopores with high air permeability that was found down to 0.45-m depth. In another U.S. study, Weil and Kremen (2007) reported that growing radish during the previous winter led to the creation of new root channels or biopores resulting in a tenfold increase in maize and soybean roots in the subsoil (0.55-m depth) compared with where no cover crop was grown.

Although the benefit of a fodder radish cover crop has been demonstrated in some studies, it is important to note that potential effect depends on soil type, soil management, and weather condition (Acuña & Villamil, 2014), but also root growth pressure will vary upon the degree of compaction (Taylor & Brar, 1991). For our studied sandy loam soils, which went from compacted to very compacted, growing the fodder radish cover crop for longer period might be needed to reveal its full potential for compaction alleviation. There is also a need to test the potential of other species to alleviate severely compacted subsoils.

4 | CONCLUSION

For the studied sandy loam soils, detrimental effects of subsoil compaction on pore volume and gas transport properties persisted for four years after completion of the experiment. Our data confirm that natural recovery of subsoil compaction is a slow process. For the compacted soils, the smaller values of the Buckingham-X exponent, PO1, r_{eff}, and the lower R-ratio at high air permeability, as well as the decrease in R-ratio with increase in pore air velocity, were clear indications that the pore system of the compacted subsoil became dominated by vertical arterial pores. Our study thus quantifies that farm-realistic field traffic induces residual and important impacts on subsoil pore functionality of temperate region till soils. The fodder radish cover crop did not significantly stimulate soil structure recovery after four years of annual establishment.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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