Two decades of no-till in the Oberacker long-term field experiment: Part II. Soil porosity and gas transport parameters

Ingrid Martínez\textsuperscript{a}, Andreas Chervet\textsuperscript{b}, Peter Weisskopf\textsuperscript{a}, Wolfgang G. Sturiny\textsuperscript{b}, Jan Rel\textsuperscript{a}, Thomas Keller\textsuperscript{a,c,*}

\textsuperscript{a}Agroscope, Department of Natural Resources & Agriculture, Reckenholzstrasse 191, CH-8046 Zurich, Switzerland
\textsuperscript{b}Bern Office of Agriculture & Nature, Soil Conservation Service, Ruetti, CH-3052 Zollikofen, Switzerland
\textsuperscript{c}Swedish University of Agricultural Sciences, Department of Soil & Environment, Box 7014, SE-75007 Uppsala, Sweden

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\section*{Abstract}
This is the second in a series of papers describing the impact of two decades of no-till in the Oberacker long-term field experiment in Switzerland. The first focused on crop yields, soil organic carbon and nutrient distributions in the soil, while this study investigated the impact on soil gas transport properties. The Oberacker long-term field experiment was established in 1994 on a sandy loam and compares two tillage systems, mouldboard ploughing (MP) and no-till (NT). Undisturbed soil cores were collected at 0.1 (topsoil) and 0.4 m depth (subsoil) from both tillage treatments. The results show that the soil pore system and gas transport properties of the NT soil were similar to those under PG for both topsoil and subsoil. In contrast, the soil under MP showed a clear stratification: $e_a$ and $k_a$ were higher in NT and PG in the topsoil, but lower in the subsoil. To determine relationships accurately described by a model derived from percolation theory. A linear relationship between $k_a$ and $e_a$ was found, but the slope was smaller than could be expected from percolation theory, in particular for subsoil, possibly because of the anisotropy of macropores. The pore system showed slightly higher specific diffusivity and much higher specific air permeability in the topsoil of MP than in NT or PG, but the relations were reversed in the subsoil. Thus it is highly important to consider both the topsoil and subsoil when tillage systems are evaluated.

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1. Introduction

No-till or direct drilling means that crops are sown without any prior loosening of the soil, where the only mechanical soil disturbance arises from the disc openers of the drill (Soane et al., 2012). No-till is practised for various reasons, including erosion protection, lower fuel consumption or higher work rates (Soane et al., 2012). Omitting soil loosening affects soil structure and various soil properties and processes and therefore has significant implications for soil functions, including crop growth.

Soil structure, i.e. the spatial arrangement of voids and soil constituents, controls important soil functions and key processes, such as water and gas transport and storage, chemical reactions, biological activity and mechanical strength, which in turn affect fluxes to roots, plant growth and crop yields (Beriss et al., 2013; Chen et al., 2014). The present study focused on soil gas transport parameters (air permeability, $k_a$, and relative gas diffusion coefficient, $D_{g}/D_{b}$), because (i) they control soil aeration and are thus a key factor for microbial activity, root growth and crop productivity (Deubel et al., 2011; Moldrup et al., 2013) and (ii) they can be used to derive information on the characteristics of the soil pore system (Gradwell, 1961; Ball, 1981; Groenevelt et al., 1984; Schjønning et al., 2002). Subsurface transport of gases through air-filled pore space predominantly occurs by diffusion (controlled by $D_{g}/D_{b}$), but near-surface pressure fluctuations induce gas transport by advection (controlled by $k_a$) (e.g. Deepagoda et al., 2011). Diffusion and advection are affected differently by pore size.

\* Corresponding author at: Agroscope, Department of Natural Resources & Agriculture, Reckenholzstrasse 191, CH-8046 Zurich, Switzerland.
E-mail addresses: thomas.keller@agroscope.admin.ch, thomas.keller@slu.se (T. Keller).
Diffusion is independent of pore size unless pores are very small, in which case gas molecules collide with the pore walls more frequently than with each other (Knudsen diffusion), while the volumetric flow rate due to transport by advection is proportional to the fourth power of the pore radius as described by the Hagen-Poiseuille law (Alaoui et al., 2011). Consequently, \( D_pD_\theta \) is a function of air-filled porosity, while \( k_d \) is controlled by the largest soil pores (Ball et al., 1988). Hence, soil pore characteristics can be obtained by combining \( D_pD_\theta \), \( k_d \) and their relationships with \( e_{soi} \), revealing aspects of pore structure such as continuity and tortuosity (Groeneveld et al., 1984; Ball et al., 1988).

Omitting soil tillage in no-till may promote the creation of continuous pores, in particular biopores, with positive effects on soil transport functions (Hartmann et al., 2012). However, this may enhance preferential flow and leaching of agrochemicals (Jarvis, 2007). Moreover, no-till may create dense topsoils, with negative impacts on soil aeration and root penetration resistance (Kay and VandenhBygaart, 2002; Schijnem and Thomsen, 2013; Nunes et al., 2015). Conventional tillage using mouldboard ploughing may result in reduced earthworm populations (Diaz-Zorita and Grove, 2002; Kay and VandenhBygaart, 2002), interruption of pores and a horizontally orientated pore system at the plough pan (Dörner and Horn, 2009; Alaoui et al., 2011; Berisso et al., 2013). It may also cause subsoil compaction by in-furrow ploughing (Lipiec and Hatano, 2003). The depth of tillage also affects the distribution of soil organic carbon in the soil profile (Blanco-Canqui and Lal, 2007), which in turn affects soil structure (Kautz et al., 2013).

The objective of this study was to investigate the long-term impact (two decades) of soil tillage (no-till versus conventional tillage including mouldboard ploughing) on the soil pore system and gas transport properties in the topsoil and subsoil in a long-term field experiment in Switzerland.

2. Materials and methods

2.1. Site description and soil sampling

The Oberacker long-term field experiment at the INFORAMA Ruetti in Zollilokfen near Berne, Switzerland (47.0’ N, 7.5’ E; 557 m a.s.l.) was established in 1994 and compares two tillage systems: mouldboard ploughing (MP; in-furrow ploughing to about 0.25 m depth before 2002 and on-land ploughing to approximately 0.15 m depth since 2003) and no-till (NT). The experiment has a split-plot design, with six experimental plots (9 m × 80 m) per treatment. Between the experimental plots there are permanent grass (PG) strips of 3 m width. Mean annual temperature at the site is 9.3 °C and mean annual precipitation is 1109 mm (Martínez et al., 2016). The soil is classified as a Eutric Cambisol with a sandy loam texture. Further details on the Oberacker long-term field experiment can be found in Martínez et al. (2016). The experiment is run with a six-year crop rotation, and the current crop rotation is: peas (Pisum sativum L.)—winter wheat (Triticum aestivum L.)—field beans (Phaseolus vulgaris L.)—winter barley (Hordeum vulgare L.)—sugar beet (Beta vulgaris L.)—silage maize (Zea mays L.), representing a typical Swiss arable crop rotation (Prasuhn, 2012). The crop rotation has received some modifications throughout the years (for details, see Martínez et al., 2016). For example, potatoes (Solanum tuberosum L.) were included until 1999 but discarded due to unsatisfactory planting technique (using direct mulch planting) and poor tuber quality in NT.

Three NT plots, three MP plots and two PG strips were sampled in spring 2013 (more than half a year after the last tillage/seedling operation in MP), i.e. 19 years after the start of the experiment. Penetrometer measurements performed prior to sampling (Martínez et al., 2016) identified two critical soil layers with substantial differences between MP and NT, namely in the topsoil at 0.05–0.2 m depth (higher resistance in NT than in MP) and in the subsoil at 0.3–0.4 m depth (lower resistance in NT than in MP) (see Fig. 4b in Martínez et al., 2016). Therefore these two layers were selected for soil sampling in the present study. Soil cores (height: 0.06 m; diameter: 0.1 m) were sampled at 0.08–0.14 m (topsoil) and 0.35–0.41 m depth (subsoil); for simplicity, thesep depths are referred to as 0.1 (topsoil) and 0.4 m (subsoil) in the remainder of this paper. At each sampling location and depth, five undisturbed soil cores were collected.

2.2. Measurement procedure for gas transport parameters

In the laboratory, the undisturbed soil core samples were slowly saturated from below and then drained stepwise to five different matric potentials, \( h \); \(-30 \) (corresponding to \( \phi \; 1.5 \); where \( \phi \; = \log (–h) \) and \( h \) in hPa), \(-60 \) (\( \phi \; 1.8 \)), \(-100 \) (\( \phi \; 2.0 \)), \(-200 \) (\( \phi \; 2.3 \)) and \(-500 \) hPa (\( \phi \; 2.7 \)). All measurements described below were performed at these five matric potentials on each sample. From the water retention measurements, the fraction of soil pores was derived and the pore diameter, \( d \) (\( \mu m \)), was estimated as \( d \approx 3000 / (–h) \) (e.g. Schijnem et al., 2002).

The soil cores were weighed at each matric potential prior to the measurements of air permeability and gas diffusivity and after oven-drying (at least 24h at 105 °C) to determine the soil water content at the different matric potentials. Air-filled porosity (\( e_{soi} \)) was calculated from the volumetric soil water content and total porosity, which was derived from soil bulk density and particle density.

2.2.1. Air permeability

Air permeability was measured using a steady-state method similar to that described by Iversen et al. (2001). The soil at the very edge of the core was carefully pressed to the cylinder walls in order to minimise leakage of air between the soil and the cylinder wall (Ball and Schijnem, 2002). The airflow was recorded when the volumetric flow rate was stabilised at a pressure of 2 hPa. Air permeability, \( k_d \), was then calculated from the volumetric flow rate and the applied pressure head using Darcy’s equation:

\[
k_d = -\frac{Qh}{A \Delta P}
\]

where \( Q \) is the volumetric flow rate (\( m^3/s \)), \( h \) is the height of the soil sample (m), \( \eta \) is the dynamic air viscosity (Pa s), \( \Delta P \) is the difference in air pressure (Pa) and \( A \) is the cross-sectional area of the soil sample (\( m^2 \)).

2.2.2. Gas diffusivity

Gas diffusivity was measured in a one-chamber apparatus similar to that described by Schijnem et al. (2013), using \( O_2 \) as the diffusing gas. The apparatus is described in detail in the Supplementary methods. The \( O_2 \) diffusion constant, \( D_pO_2 \), was derived from the relationship between time and the logarithm of the \( O_2 \) concentration difference between chamber and ambient air by assuming steady state diffusion as described in Schijnem et al. (2013):

\[
D_p = -\left( h_5 \times h_c \times \frac{A_c}{A_s} \right) \frac{\ln (\frac{\Delta C}{\Delta C_0})}{t}
\]

where \( \Delta C_0 \) is the difference in \( O_2 \) concentration between the two ends of the sample (i.e. between the \( O_2 \) concentration in the chamber and ambient \( O_2 \) concentration), \( \Delta C_0 \) is the initial difference in \( O_2 \) concentration between the two ends of the sample, \( h_5 \) is the height of the cylindrical sample, \( h_c \) is the height of the cylindrical chamber, \( A_s \) is the cross-sectional area of the
sample, $A_0$ is the cross-sectional area of the diffusion chamber and $t$ is time. This solution does not take into account gas storage in the sample. However, with the dimensions of the diffusion apparatus and considering that our interest was primarily in diffusion under moist soil conditions, the error should be small (Schjønning et al., 2013). The measurements were corrected to a standard temperature, $T_0$, of 293 K (20°C) and a standard air pressure, $p_0$, of 1000 mbar using the equation (Bakker and Hidding, 1970):

$$D_p = D_p^* \left( \frac{T_0}{T_a} \right)^{1.75} \left( \frac{p_a}{p_0} \right)$$

where $D_p^*$ is the actual measured $D_p$ (obtained from Eq. (2)) at actual measured temperature ($T_a$) and air pressure ($p_a$). The relative gas diffusion coefficient, $D_p/D_0$, was then obtained by dividing $D_p$ by the gas diffusion coefficient of $O_2$ in free air, $D_0$ (e.g. Schjønning et al., 2011).

### 2.3. Calculations of soil pore characteristics

From the measurements of $D_p/D_0$ and $e_a$, the ‘specific diffusivity’ $C_D$ also referred to as ‘diffusion efficiency’ (Kühne et al., 2012) was calculated (Gradwell, 1961) as:

$$C_D = \frac{D_p/D_0}{e_a}$$

The specific diffusivity of a pore system consisting of parallel straight tubes (capillary tubes model) is $C_D=(D_p/D_0)/e_a=1$, while 0 < $C_D$ < 1 for real soils. From the measurements of $k_s$ and $e_a$, the ‘specific air permeability’ $C_A$ (Groenevelt et al., 1984), (also referred to as ‘pore organisation’ (Blackwell et al., 1990) or ‘C2’ (Ball et al., 1988)) was obtained as:

$$C_A = \frac{k_s}{e_a}$$

The terms ‘specific diffusivity’ and ‘specific air permeability’ are used here, because the terms ‘efficiency’ or ‘pore organisation’ could be misleading – the highest possible efficiency or pore organisation implies a ‘pipe-like’ pore system, which may not be desirable from a soil structure and soil quality point of view because large parts of the soil matrix could be bypassed (preferential flow). On the other hand, pipe-like pores ensure adequate aeration of the subsoil. Consequently, optimum conditions may be obtained in an intermediate specific diffusivity and specific air permeability. Finally, we calculated $C_3$ (Groenevelt et al., 1984; Ball et al., 1988):

$$C_3 = \frac{k_s}{e_a}$$

and $P$ (Kawamoto et al., 2006a; Eden et al., 2011):

$$P = \frac{k_s}{D_p/D_0}$$

which have been suggested as soil structure indices. $C_3$ and $P$ reveal similar information and, in the case of $D_p/D_0 = e_a^2$ (corresponding to the Buckingham (1904) model), $C_3 = P$.

### 2.4. Modelling gas transport properties as a function of air-filled porosity

In this study we investigated the applicability of equations derived from percolation theory that describe how the relative gas diffusivity coefficient and air permeability evolve as a function of air-filled porosity, by fitting these equations to our experimental data. Percolation theory can be used to describe properties at macroscopic scale (e.g. permeability) that are determined by the connectivity of the elements (e.g. bonds, which could represent pores) of a system (e.g. porous media, such as soil). A central feature of percolation theory is that the volumetric fluid flow, $Q$, is determined as (Berkowitz and Ewing, 1998):

$$Q \propto (N - N_c)^{\mu}$$

where $N$ is the number of bonds, $N_c$ is the critical number of bonds required for fluid flow to occur and $\mu$ is an exponent. Thus the network (e.g. a soil pore network) can only conduct a fluid if $N > N_c$, while there is no flow through the system (e.g. from the bottom to the top of a soil sample) at $N < N_c$. This property is known as the percolation threshold. See Berkowitz and Ewing (1998) for further reading on percolation theory and its application in soil physics.

Gas diffusivity in porous media can be modelled as (Ghanbarian and Hunt, 2014):

$$D_p/D_0 = \left[ \frac{e_a - e_c}{1 - e_c} \right]^\mu$$

where $e_c$ is the percolation threshold and $\mu$ is the scaling exponent. Eq. (9) is identical to the empirical equation proposed by Troeh et al. (1982). The percolation threshold can be interpreted as the minimum air-filled porosity required to allow for gas transport by diffusion. The percolation threshold depends on the pore structure, pore size distribution and pore continuity (Ghanbarian and Hunt, 2014). We fitted Eq. (9) to our experimental data by non-linear least squares fitting.

The change in air permeability, $k_s$, with air-filled porosity, $e_a$, can be described based on percolation theory as (Ghanbarian-Alavijeh and Hunt, 2012):

$$k_s(e_a) = k_s(e_a = \phi) \left[ \frac{e_a - e_c}{\phi - e_c} \right]^\tau$$

where $e_c$ is the percolation threshold, $\tau$ is the scaling exponent and $\phi$ is the porosity. Note that $e_c$ may differ from $e_a$ in Eq. (9). According to Ghanbarian-Alavijeh and Hunt (2012), any measured $k_s$ can be used as a reference point in Eq. (10) if $k_s(\phi)$ is not available. Since $k_s(\phi)$ was not measured for our samples, we fitted (Ghanbarian-Alavijeh and Hunt, 2012):

$$k_s(e_a) = k_s(e_a = 0.500) \left[ \frac{e_a - e_c}{0.500 - e_c} \right]^\tau$$

to our data, where $e_{0.500}$ is the air-filled porosity at −500 hPa (i.e. the driest condition used in this work) and $k_s(0.500)$ is our reference point.

An interesting aspect of percolation theory is that the exponent ($\mu$ in Eq. (8), $\mu$ in Eq. (9), $\tau$ in Eqs. (10)–(11)) has the same value for many systems, which is known as universality (Berkowitz and Ewing, 1998). In theory, the exponent takes values of 1.3 and 2 in two and three dimensions (two and three-dimensional flow), respectively (Ghanbarian-Alavijeh and Hunt, 2012; Ghanbarian and Hunt, 2014). Different values for the exponent characterise non-universal behaviour (Berkowitz and Ewing, 1998). One of the basic assumptions in percolation theory is that the medium is infinite, stationary and random (Berkowitz and Ewing, 1998).

### 2.5. Statistical analysis

Soil porosity and gas transport parameters were analysed using the InfoStat statistical analysis software (Di Rienzo et al., 2009). Air permeability data were log-transformed before analysis. A split-plot linear mixed model was used, with fixed effects of tillage treatment, depth, $pF = \log_{(10)}(h)$, where $h$ is the matric potential) and tillage treatment-by-depth interaction, and random effects of plots. Means were tested using the Tukey method at significance level $p < 0.05$. 
Table 1
Characteristics of the topsoil (0.1 m) and subsoil (0.4 m) at the Oberacker site in plots with mouldboard ploughing (MP), no-till (NT) and permanent grass (PG). Clay <0.002 mm; silt 0.002–0.05 mm; sand 0.05–0.2 mm; OM: organic matter content. Numbers in brackets indicate standard error.

<table>
<thead>
<tr>
<th>Soil characteristics</th>
<th>Topsoil, 0.1 m</th>
<th>Subsoil, 0.4 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MP</td>
<td>NT</td>
</tr>
<tr>
<td>Clay (% by weight)</td>
<td>18.2 (1.2)</td>
<td>19.0 (1.7)</td>
</tr>
<tr>
<td>Silt (% by weight)</td>
<td>22.7 (0.5)</td>
<td>22.6 (1.8)</td>
</tr>
<tr>
<td>Sand (% by weight)</td>
<td>59.1 (0.5)</td>
<td>58.4 (3.3)</td>
</tr>
<tr>
<td>OM (% by weight)</td>
<td>2.7 (0.2)</td>
<td>2.3 (0.3)</td>
</tr>
<tr>
<td>Dry bulk density (Mg m⁻³)</td>
<td>1.35 (0.02)</td>
<td>1.47 (0.02)</td>
</tr>
<tr>
<td>Particle density (Mg m⁻³)</td>
<td>2.59 (0.03)</td>
<td>2.60 (0.03)</td>
</tr>
</tbody>
</table>

3. Results

3.1. Bulk density, porosity and pore size distribution

In the topsoil, bulk density (BD) was significantly lower \( (p < 0.05) \) in MP (1.35 Mg m⁻³) than in NT (1.47 Mg m⁻³) and PG (1.46 Mg m⁻³). In the subsoil, BD was higher in MP (1.54 Mg m⁻³) than in NT and PG (1.49 and 1.48 Mg m⁻³, respectively), although the differences were not significant (Table 1). Two aspects of this are interesting; first, NT and PG showed similar BD and second, there was no significant difference in BD between topsoil and subsoil in PG and NT, while there was a clear stratification in MP with lower BD in the topsoil. The fractions of pores derived from water retention measurements are presented in Fig. 1. Interestingly, the volume of pores >100 μm was larger in the subsoil than in the topsoil, especially for NT and PG (Fig. 1). Pores >100 μm could be biopores (root and earthworm channels) or inter-aggregate pores such as voids between fragments formed during tillage. In the topsoil, the lower BD in MP compared with NT and PG was mainly due to the larger volume of pores >100 μm, as there was little difference between treatments for the other pore size classes (Fig. 1). Hence, plant-available water (i.e. water stored in pores with equivalent diameter between 0.2 and 30 μm, corresponding to a ϕ f range of 2–4.2; e.g. Reynolds and Clarke Topp, 2008) was similar in all treatments. The volume of the smallest pore fraction measured (d <6 μm) was much smaller in the subsoil compared with the topsoil, which is associated with the lower soil organic carbon content of the subsoil (Dexter et al., 2008). Pores smaller than 3 μm store water and constitute protective pores where smaller organisms (bacteria, protozoa) take refuge from predation (e.g. Brussaard and van Faassen, 1994; Schjønning et al., 2002).

In agreement with Fig. 1, MP showed significantly higher air-filled porosity, \( e_a \), than PG and NT in the topsoil at any given matric potential, but in the subsoil PG and NT showed the highest values (Fig. 2a–b). The line in Fig. 2a–b is \( e_a = 0.1 \) m³ m⁻³ which is a critical lower limit for satisfactory root growth (Grable and Siemer, 1968), as discussed in Section 4.3.

3.2. Gas transport properties: relative gas diffusion coefficient and air permeability

The relative gas diffusion coefficient \( (D_g/D_w) \) for the five matric potentials in the topsoil and subsoil was similar for PG and NT (Fig. 2c–d). In the topsoil, \( D_g/D_w \) was significantly higher in MP than in PG and NT, but the relationship was reversed (i.e. lower \( D_g/D_w \) in MP) in the subsoil (Fig. 2c–d). The horizontal lines in Fig. 2c–d indicate critical thresholds for soil aeration according to Stepiniewski (1980, 1981) \( (D_g/D_w = 0.005) \) and (Schjønning et al., 2003) \( (D_g/D_w = 0.02) \), as discussed in Section 4.3.

The data in Fig. 2e–f show log \( k_a \), as a function of ϕ. According to Fish and Koppi (1994), soils that are below log \( k_a < 13 \) (corresponding to \( k_a = 20 \) μm²), indicated by horizontal lines in Fig. 2e–f, are considered poorly aerated. Air permeability in the topsoil was higher in MP than in NT and PG at all matric potentials. The lower air permeability for PG and NT than MP in the topsoil is consistent with the smaller proportion of large pores (Fig. 1). As for \( D_g/D_w \), the relationship was also reversed for \( k_a \) in the subsoil, i.e. higher \( k_a \) in NT and PG than in MP (Fig. 2e–f). It is interesting that in NT and PG, \( D_g/D_w \) and \( k_a \) were higher in the subsoil than in the topsoil. In contrast, in MP \( D_g/D_w \) and \( k_a \) were higher in the topsoil than in the subsoil.

3.3. Soil structure indices derived from gas transport properties

The different soil pore characteristics/soil structure indices (Eqs. (4)–(7)) obtained from our data, as average values for all five matric potentials, are presented in Fig. 3. The indices did not vary greatly with matric potential and the relationships between the treatments did not change with matric potential (not shown). In MP, both the specific air permeability (Fig. 3a) and the specific diffusivity (Fig. 3b) were significantly larger in the topsoil, but significantly smaller in the subsoil, compared with NT and PG. The difference between MP and NT or PG was larger for \( C_A \) (Fig. 3a) than for \( C_p \) (Fig. 3b), especially in the topsoil.

As Fig. 3c and d show, there were differences between treatments for the topsoil (higher \( C \) and \( P \) in MP), but not for the subsoil (but values for MP were lowest). The values for \( C \) and \( P \) were similar in the subsoil, while the values for \( C \) in the topsoil were higher than those for \( P \) by a factor of 1.4–2.3. As mentioned elsewhere, \( C = P \) for \( D_g/D_w = e_a^{-2} \). The higher values for \( C \) than \( P \) are explained by disproportionately high values of \( k_a \) in relation to \( e_a \), caused by single structural pores (inter-aggregate pores, biopores) in the topsoil.

Fig. 1. Fraction of pores derived from water retention measurements influenced by no-till (NT), mouldboard ploughing (MP) and permanent grassland (PG) at 0.1 and 0.4 m depth.

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Fig. 2. (a,b) Air-filled porosity, $\varepsilon_a$, (c,d) relative gas diffusion coefficient, $D_p/D_0$, and (e,f) air permeability, $k_a$, for the three soil management systems (NT: no-till; MP: mouldboard ploughing; PG: permanent grassland) at 0.1 m (a,c,e) and 0.4 m depth (b,d,f) as a function of $pF$ (=log (-h), where h is the matric potential). Note that NT and PG are slightly displaced for better readability, and that the legends of the top panels apply to all data shown. The dashed lines represent critical limits for $\varepsilon_a$ (Grable and Siemer, 1968), $D_p/D_0$ (Stepniewski, 1980, 1981; Schjønning et al., 2003), and $k_a$ (Fish and Koppi, 1994). Error bars indicate ±1 standard error.
3.4. Modelling gas transport properties as a function of air-filled porosity: percolation threshold and scaling exponent

The relative gas diffusion coefficient as a function of air-filled porosity is presented in Fig. 4. The line in Fig. 4 shows the fit of Eq. (9) to the data from all treatments and depths. The average values for $\varepsilon_t$ and $\mu$ (Eq. (9)) per soil management system and soil layer are given in Table 2. There were no significant differences in $\mu$ between the different soil management systems, but a trend for higher (closer to 2) values in the subsoil. The $D_0/D_\infty$-associated percolation threshold was found to be smallest for PG and largest for MP, and $\varepsilon_t$ was generally higher in the subsoil than in the topsoil. On average for all treatments and layers, we found a value for $\varepsilon_t$ of 0.006, i.e. the average $\varepsilon_t$ was close to zero and the average $\mu$ close to 2. For $\varepsilon_t = 0$ and $\mu = 2$, Eq. (9) equals the Buckingham (1904) model (i.e. $D_0/D_\infty = \varepsilon_t^2$). Consequently, the Buckingham (1904) relation fitted our data almost equally well (not shown). It is interesting that the rather simple Eq. (9) fitted our data well, irrespective of soil management or soil layer (Fig. 4; Table 2).

Air permeability as a function of air-filled porosity is shown in Fig. 5 in log–log scale. The graph reveals similar slopes of the log $k_a$ vs log $\varepsilon_t$ relationship for all subsoils, while the slopes for the topsoils vary (larger slope for MP and PG, smaller slope for NT). The $k_a$-associated percolation thresholds and scaling exponents for the different soil managements and soil layers are summarised in Table 2. The percolation threshold was smaller in the topsoil than in the subsoil. In the topsoil, $\varepsilon_t$ was similar in MP and NT. In the subsoil, the lowest $\varepsilon_t$ was found for MP and the highest $\varepsilon_t$ for NT. For all treatments and layers, we obtained an average value for $\varepsilon_t$ of 0.031. The $k_a$-associated scaling exponents were close to 2 for the
topsoil of MP and PG, while they were <1 for the topsoil of NT and for all subsols. On average (all treatments, both depths), we obtained a value for \( t \) of 1.1 (Table 2).

4. Discussion

4.1. Air-filled pore space, soil gas transport capability and soil structure indices

The measurements of \( \varepsilon_a, k_a, \) and \( D_0/D_0 \) revealed consistently higher values for MP than for NT or PG in the topsoil, but consistently lower values for MP than for NT or PG in the subsoil (Fig. 2). Similar values of \( \varepsilon_a, k_a \) and \( D_0/D_0 \) were observed for NT and PG (Fig. 2). A distinct difference in soil pore properties between topsoil and subsoil was found for MP (higher values in the topsoil than in the subsoil), while there was a smaller difference between topsoil and subsoil for NT and PG (similar values or higher values in the subsoil than in the topsoil) (Figs. 2 and 3).

Differences in \( C_A \) and \( C_D \) (Fig. 3a–b) indicated (i) higher connectivity, higher continuity and lower tortuosity (or any combination), especially for macropores because the differences were larger for \( C_A \) in the topsoil of MP compared with the topsoil of either NT or PG, and (ii) lower connectivity, lower continuity and higher tortuosity (or any combination) in the subsoil of MP compared with the subsoil of NT and PG. The pore structures of NT and PG were similar for both depths. In MP, the volume of macropores was not lower in the subsoil than in the topsoil (Fig. 1), despite the lower \( k_s \) in the subsoil. Hence, the MP macropore system had higher connectivity, higher continuity or lower tortuosity in the topsoil compared with the subsoil. NT and PG had lower macroporosity in the topsoil than in the subsoil (Fig. 1), which correlates with the lower \( k_s \) in the topsoil (Fig. 2e–f).

The values of \( P \) recorded here (Fig. 3d) were 3- to 5-fold higher than the \( P^* \) reported by Kawamoto et al. (2006a) for Danish loamy soils. The soils used by Kawamoto et al. (2006a), which are described in Kawamoto et al. (2006b), had on average a slightly lower content of silt and a correspondingly higher content of sand (59–96% sand compared with 57–65% in our study), while the clay content was similar. Their soil also had a lower soil organic matter content. The higher values of \( P \) found in the Oberacker soil indicate a higher proportion of continuous macro pores, e.g. biopores, than in the soils used by Kawamoto et al. (2006a). Thirteen out of the 22 soils in their dataset had a very high sand content (70–96%), and macropores may be poorly connected in sandy soils (Håkansson, 2005).

4.2. Percolation threshold and scaling exponent

The percolation threshold for advective air flow (\( \varepsilon_p = 0.031 \)) in the present study was almost one order of magnitude larger than the percolation threshold for gas diffusion (\( \varepsilon_p = 0.006 \)) (Table 2). The average \( \varepsilon_p \) found here (\( \varepsilon_p = 0.006 \)) was about 10-fold smaller than the average value found by Ghanbarian and Hunt (2014), who analysed a large dataset including intact and remoulded samples. Our samples had a smaller total porosity, \( \Phi \), as well as smaller \( \varepsilon_{min} \) and \( \varepsilon_{max} \) (minimum and maximum \( \varepsilon_a \), respectively) than most soils included in the study by Ghanbarian and Hunt (2014). Furthermore, \( \varepsilon_a \) in our study was similar to values obtained by Ghanbarian and Hunt (2014) for certain soils. The average \( \varepsilon_a \) value of 0.031 found for our data was similar to the values presented in Ghanbarian-Alavijeh and Hunt (2012).

The \( D_0/D_0 \)-associated scaling factor, \( \mu \) (Eq. (9)), was close to the theoretical value of \( \mu = 2 \) for three-dimensional flow (Ghanbarian and Hunt, 2014), with little variation among treatments and soil depths (Table 2). In contrast, the \( k_s \)-associated scaling factor, \( t \) (Eqs. (10)–(11)), varied between 0.35 and 2.08, with an overall average of

Table 2

<table>
<thead>
<tr>
<th>Soil management system and depth</th>
<th>( \varepsilon_p )</th>
<th>( \mu )</th>
<th>( \varepsilon_a )</th>
<th>( t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mouldboard ploughing</td>
<td>0.009 (0.013)</td>
<td>1.80 (0.00)</td>
<td>0.031 (0.053)</td>
<td>2.08 (0.96)</td>
</tr>
<tr>
<td>No-till</td>
<td>0.003 (0.005)</td>
<td>1.87 (0.08)</td>
<td>0.032 (0.031)</td>
<td>0.64 (0.47)</td>
</tr>
<tr>
<td>Permanent grass</td>
<td>0.000 (0.000)</td>
<td>1.90 (0.14)</td>
<td>0.000 (0.000)</td>
<td>2.05 (1.40)</td>
</tr>
<tr>
<td>Mean Topsoil</td>
<td>0.004</td>
<td>1.86</td>
<td>0.021</td>
<td>1.59</td>
</tr>
<tr>
<td>Subsoil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mouldboard ploughing</td>
<td>0.014 (0.024)</td>
<td>1.98 (0.16)</td>
<td>0.000 (0.000)</td>
<td>0.87 (0.26)</td>
</tr>
<tr>
<td>No-till</td>
<td>0.008 (0.013)</td>
<td>1.90 (0.18)</td>
<td>0.088 (0.020)</td>
<td>0.35 (0.30)</td>
</tr>
<tr>
<td>Permanent grass</td>
<td>0.000 (0.000)</td>
<td>2.06 (0.08)</td>
<td>0.037 (0.046)</td>
<td>0.55 (0.57)</td>
</tr>
<tr>
<td>Mean Subsoil</td>
<td>0.007</td>
<td>1.98</td>
<td>0.042</td>
<td>0.59</td>
</tr>
<tr>
<td>Mean Mouldboard ploughing</td>
<td>0.012</td>
<td>1.89</td>
<td>0.015</td>
<td>1.48</td>
</tr>
<tr>
<td>Mean No-till</td>
<td>0.005</td>
<td>1.89</td>
<td>0.060</td>
<td>0.50</td>
</tr>
<tr>
<td>MeanPermanent grass</td>
<td>0.000</td>
<td>1.98</td>
<td>0.019</td>
<td>1.30</td>
</tr>
<tr>
<td>Mean</td>
<td>0.006</td>
<td>1.92</td>
<td>0.031</td>
<td>1.09</td>
</tr>
</tbody>
</table>
Similarly, Kawamoto et al. (2006a) found smaller exponents (called $\eta$ in their publication) for $k_b$ than for $D_p/\Omega_0$. For their Gorslev soil, which has a similar texture to our soil (see Kawamoto et al., 2006b), they obtained $\eta = 2.02$ for gas diffusion and $\eta = 1.34$ for air permeability (Kawamoto et al., 2006a).

### 4.3. Soil aeration and implications for plant growth

Soil aeration, i.e. gas exchange between the atmosphere and the soil, which supports aerobic respiration by soil biota (plant roots, microorganisms) is a dynamic process that depends on various factors, including soil structure and soil moisture (and thereby the volume of air-filled pores and the gas transport capability of soil, which is governed by $a_b$ and $D_p/\Omega_0$), temperature, the composition of soil air (e.g. the concentrations of $O_2$ and $CO_2$) and $O_2$ consumption (Boone and Veen, 1994; Stepieniewski et al., 1994).

The air-filled porosity and gas transport properties ($a_b$ and $D_p/\Omega_0$) are key properties that control the potential soil aeration, as they impose the soil physical constraints on soil aeration. Generally, high $D_p/\Omega_0$ and high $a_b$ would facilitate soil-atmosphere gas exchange (i.e. replenishment of $O_2$ from the atmosphere into the soil and removal of toxic gases from the root zone), while low $D_p/\Omega_0$ and low $a_b$ would increase the risk of anoxic conditions with negative impacts on root growth and a potential increase in greenhouse gas emissions.

Various lower limits for adequate soil aeration for soil physical properties have been proposed. The critical thresholds that have been established state that soil aeration is deficient if $a_b < 0.1 \text{ m}^3 \text{ m}^{-3}$ (Grable and Siemer, 1968) and if $D_p/\Omega_0 < 0.005$ (Stepniowski, 1980, 1981) to 0.02 (Schjønning et al., 2003). We note that $a_b = 0.1 \text{ m}^3 \text{ m}^{-3}$ corresponds to $D_p/\Omega_0 = 0.01$ on applying the Buckingham (1904) model, viz. $D_p/\Omega_0 = a_b^{0.2}$. Boone (1986) established a lower and upper critical limit for oxygen diffusion to ensure sufficient aeration for low and high $O_2$ consumption, corresponding to $D_p = 7.5 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ for the lower limit and $D_p = 7.5 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$ (Stepniowski et al., 1994), resulting in $D_p/\Omega_0 = 0.0037$ for the lower limit and $D_p/\Omega_0 = 0.073$ for the upper limit. The upper limit seems rather high, and was not reached even at the driest condition (-500 hPa) in our soil (Fig. 2). The lower limit is only slightly lower than the critical limit proposed by Stepieniewski (1980, 1981). The upper and lower critical limits suggested by Boone (1986) clearly show that soil physical properties, such as $D_p/\Omega_0$, are a measure of potential aeration, while the actual soil aeration depends on the actual $O_2$ demand (i.e. the $O_2$ consumption), among other factors. Similarly, drawing conclusions on actual greenhouse gas emissions (e.g. $N_2O$, $CO_2$) from values of $D_p/\Omega_0$ is not straightforward, because additional factors such as temperature, microbial communities and N and C availability control aeration (Ball, 2013). Since gas transport in soil primarily occurs by diffusion (Stepniowski et al., 1994), lower limits for $a_b$ are less well established. However, a soil with $a_b = 1 \mu m^3$ is considered effectively impermeable (Ball et al., 1988), and $a_b < 20 \mu m^3$ is suggested to limit soil aeration (Fish and Koppi, 1994).

As regards the critical threshold for $a_b$, NT was below the critical threshold in the topsoil when the soil was wetter than $pF 2$, i.e. wetter than field capacity, and PG was at critically low levels at $pF \leq 2.3$ (Fig. 2a–b). In contrast, $a_b$ in MP was $\geq 0.1 \text{ m}^3 \text{ m}^{-3}$ at all matric potentials studied (Fig. 2a–b). Based on the critical threshold of $D_p/\Omega_0 = 0.02$ for soil aeration proposed by Schjønning et al. (2003), our measurements indicated that critically low levels of $D_p/\Omega_0$ were reached in the topsoil of NT and PG at nearly all matric potentials and in the subsoil of MP at $pF \leq 2$ (Fig. 2c–d). Although $D_p/\Omega_0$ was always above the critical threshold of $D_p/\Omega_0 = 0.005$ suggested by Stepieniewski (1980, 1981) in all treatments and at both depths. Note that the critical limit suggested by Schjønning et al. (2003) was
obtained on sandy soil, while our soil was a sandy loam. In the topsoil, PG and NT displayed \( k_s \) values below log \( k_s <1.3 \) at \( pF <2 \) (NT) and at \( pF <2.3 \) (PG) (Fig. 2e–f), which may limit soil aeration (Fish and Koppi, 1994). However, the cited critical limits were derived from conventionally tilled soils and Reichert et al. (2009) suggest that different critical limits of soil physical conditions for root growth may apply to no-till soils.

Nevertheless, at a given matric potential, our results clearly indicate that the gas transport capability was: (i) highest under MP in the topsoil, but (ii) lowest under MP in the subsoil. The results also suggest that \( D_P/D_h \) and \( k_s \) of the topsoil were at critically low levels in NT and PG, which we attributed to field traffic in combination with lack of soil loosening (no-till). In contrast, \( D_P/D_h \) and \( k_s \) were low in the subsoil of MP, which we attributed to the actions of mouldboard ploughing (high mechanical subsoil stresses during in-furrow ploughing, soil smearing at the topsoil-subsoil interface, killing of earthworms due to ploughing). Tillage, in particular mouldboard ploughing, is known to have a negative impact on pore continuity (especially on the continuity of biopores) at the topsoil-subsoil interface, and this discontinuity may impair root growth (Munkholm et al., 2005; Olesen and Munkholm, 2007). In contrast, reduced tillage may not be as detrimental to earthworm populations, and reduced tillage may result in higher macropore volumes in the subsoil than in the topsoil (Kautz et al., 2013).

Biological activity, root density and nutrient concentrations are greater in the topsoil than in the subsoil, which reflects a greater impact of the topsoil than the subsoil on crop performance (Kautz et al., 2013; Uteau et al., 2013). Hence, the higher soil porosity and higher gas transport capability (higher \( k_s \) and higher \( D_P/D_h \)) of the topsoil in MP than in NT would indicate more favourable crop growth conditions in MP, especially during early crop development. However, the topsoil is typically drier (i.e. more negative matric potential or higher \( pF \) value) than the subsoil due to higher root water uptake in the topsoil, and so the critically low gas transport capability at moist conditions in NT and PG may be relevant only under limited time periods, while the subsoil in MP may more often be at critical levels in terms of gas transport. Furthermore, the soil may be more prone to slaking and subsequent surface sealing in MP due to soil destabilisation during fragmentation by tillage, which could drastically reduce soil aeration even under dry conditions (Hakansson et al., 2012). Gut et al. (2015) reported no difference in the long-term average soil macroporosity potential at 0.3 m depth between NT and MP. However, Chervet et al. (2006) found on average slightly more moist conditions in NT than in MP in maize during the summer months (June to August) based on tensiometer and TDR measurements during the period 1998–2005.

The contribution of subsoil to crop growth is not negligible. For example, subsoil compaction is known to result in permanent yield decline (e.g. Hakansson and Reeder, 1994) and crops are known to acquire nutrients from the subsoil (Kautz et al., 2013). Different crops may be more or less dependent on the subsoil, and the dependency is affected by the climate and the weather conditions. In the Oberacker long-term field experiment, cereals (winter barley and winter wheat) and legumes (field beans and peas) produce higher yields in NT, while tuber and root crops (potatoes and sugar beet) yield more in MP (Martinez et al., 2016). The lower yield of tuber and root crops may be related to the higher topsoil compactness (higher BD) in NT than in MP. Cereals and legumes seem to not have suffered from the dense topsoil in NT and their roots may have been able to better explore the subsoil in NT than in MP. The higher density in the topsoil of NT may also have been compensated for with regard to crop productivity by the higher nutrient and organic carbon concentrations in the uppermost soil layers in NT (Martinez et al., 2016). The potential specific uptake rate (per unit root length) of nutrients is unlikely to be affected by the tillage system (Boone and Veen, 1994).

The higher macroporosity and associated higher \( D_P/D_h \) and \( k_s \) in the subsoil under NT and PG compared with MP may be associated with greater earthworm abundances. Results after 10 experimental years of the Oberacker long-term field experiment (Maurer-Troxler et al., 2005) showed that the earthworm biomass in MP was only 49.5% of that in NT. Unpublished data (Maurer-Troxler et al., 2015) from 2014, i.e. from the 19th experimental year, show similar trends. These results are in line with findings in other studies that the earthworm population in conventional tillage is about half that in no-till (e.g. Lagerlöf et al., 2012). In particular, anecic earthworms such as Lumbricus terrestris are present at much higher abundance in NT than in MP in the Oberacker experiment (Maurer-Troxler et al., 2005), resulting in a higher number of intact, continuous bio-channels in NT. This correlates with the higher gas transport capability (i.e. higher \( D_P/D_h \) and higher \( k_s \)) found in the subsoil in NT compared with MP. Earthworm bioturbation increases the access to subsoil for crop roots in arable soils (Kautz et al., 2013), and may therefore contribute to the higher (although not significantly) overall average yield under NT found for the Oberacker long-term field experiment (Martinez et al., 2016).

5. Conclusions

Soil pore structure and gas transport properties (air permeability, \( k_s \), and relative gas diffusion coefficient, \( D_P/D_h \)) 19 years after initiation of the Oberacker long-term field experiment were found to be similar in the no-till (NT) plots and the grass strips between the experimental plots (PG), while the soil pore structure was markedly different in the mouldboard ploughed soil (MP). This suggests that the soil structure in NT evolves towards that in a natural grassland. There was clear stratification in gas transport properties in MP, caused by a relatively loose topsoil and a compact subsoil, while the differences between the topsoil and subsoil were small for NT and PG. In the topsoil, there were indications of higher specific diffusivity and much higher specific air permeability in MP than in NT and PG, reflecting higher continuity, higher connectivity and lower tortuosity, especially of macropores in MP. In the subsoil, the gas transport capability was lower in MP than in NT and PG, presumably due to fewer continuous biopores. The gas transport properties reached low values under moist conditions in the topsoil of NT and PG and in the subsoil of MP, which may restrict soil aeration. Thus it is highly important to include the properties of the subsoil when evaluating tillage systems, as the results can be diametrically opposed to those in the topsoil and can affect different crops in different ways.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2016.05.020.