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IN SITU, ON-SITE AND LABORATORY MEASUREMENTS OF SOIL AIR PERMEABILITY: BOUNDARY CONDITIONS AND MEASUREMENT SCALE

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The measurement of soil air permeability is a fast and easy method that can be used in different ways to characterize the soil. An air permeameter was constructed in order to measure air permeability (k_a) *in situ*, on-site (exhumed soil samples), and in the laboratory on a wide range of Danish agricultural soils. Two different sizes of sample rings were used (100 cm^3 and 3140 cm^3). The device was initially tested in the laboratory on repacked soil samples to evaluate dependency of k_a on sample size. The results showed consistent values of k_a for both sample sizes, indicating only little scale effect. In the field, air permeability was measured *in situ* and on-site using large sample rings. Air permeability *in situ* was determined by using a "shape factor" taking into account boundary conditions at the lower end of the ring while assuming isotropic soil conditions. An expression for the shape factor developed by Liang et al. (1995) was used. The results from the two measurement methods compared well, indicating reliable air permeability values using the expression of Liang et al. for the soils studied. Air permeability in structured soil measured using exhumed samples of different size showed that small samples generally yielded lower values and higher variability in k_a than large samples, in accordance with the concept of a representative elementary volume. (Soil Science 2001;166:97–106)

Key words: Air permeability, undisturbed soil, boundary conditions, scale effects, representative elementary volume.

THE quality and reliability of prediction by simulation models describing subsurface processes rely heavily on the quality of the input data relating to the soil characteristics. The increased use of distributed models in connection with geographical information systems has increased the amount of data needed and focused on knowledge of the spatial variability of soil physical parameters. When modeling dynamic water transport through the unsaturated zone, the saturated hydraulic conductivity (K_w) is an essential parameter. Measurements of K_w are often time demanding, and the quality of the measurements may not be proportional to the amount of time used. Determination of K_w from more easily obtainable and/or readily available soil properties has been proposed in different studies (Gimenez et al., 1997; Mckenzie and Jacquier, 1997; Poulsen et al., 1999; Timlin et al., 1999). Relating K_w to (intrinsic) air permeability (k_a) has been proposed by Schjønning (1986), Riley and Ekeberg (1989), Blackwell et al. (1990), Loll et al. (1999).

Air permeability can be used to determine the pore characteristic of soils. Blackwell et al. (1990) used k_a and air-filled macroporosity to characterize the soil and used this relationship to identify changes in soil structure caused by soil management practices and biological activity. Ball (1981) used gas diffusivity, k_a and air-filled porosity to describe the continuity and tortuousity of macropores in the soil. Roseberg and McCoy (1990) measured k_a at different water

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contents at and near saturation to analyze macropore behavior of the soil. Knowledge of k_a is also useful in relation to modeling soil vapor extraction systems for remediation of soils contaminated with volatile organic compounds (Poulsen et al., 1996; Moldrup et al., 1998).

Several studies have proposed methods for measuring k_a *in situ* (Kirkham, 1947; Grover, 1955; Steinbrenner, 1959; Green and Fordham, 1975; Bowen, 1966 and 1985; Fish and Koppi, 1994). Grover (1955) developed a simple air permeameter that consisted of a hollow float connected to the soil sample by a tube and an annular water-filled reservoir. Steinbrenner (1959) developed a portable air permeameter with the purpose of measuring macroscopic pore space *in situ*. Green and Fordham (1975) developed an air permeameter with a diameter of 5.1 cm to be used for soil samples. The permeameter consisted of a small cylinder containing compressed air controlled by precision pressure regulators. By means of this device, k_a could be measured with the sample placed *in situ* in the soil or with the core exhumed. Bowen (1966, 1985) used a modified version of Grover's (1955) air permeameter, where the process of reading the instrument was improved by incorporating a sensitive flowmeter and manometer. Fish and Koppi (1994) constructed an air permeameter with a sample diameter of 18 cm and measured the pressure difference through the soil sample with a digital manometer.

When measuring k_a *in situ* (i.e., with the sample still in place in the soil), the air pressure at the lower end of the sample is not known because the air still has to flow through an (unknown) volume of soil before it reaches the soil surface. Measurements of k_a carried out by Green and Fordham (1975) showed that the flow rate for exhumed cores was 1.4 to 2.5 times larger than for *in situ* cores using the same pressure difference; they concluded that k_a measured *in situ* required careful interpretation of the results. The consequence of the lack of boundary conditions means that a "shape factor" has been introduced in the calculation of k_a, talking into account the geometry of the flow lines when the air leaves the lower part of the measuring cylinder in the soil. From experimental data using an electrolytic model (Frevert, 1948), Grover (1955) produced a nomogram for estimating the shape factor for different sample diameters and sample depths. Kirkham et al. (1958) later discovered an error in Grover's nomograms, such that the ratio between the shape factor and the sample diameter was four to five times too large, in agreement with results from Boedicker (1972). Liang et al. (1995) carried out a thorough investigation using finite element modeling to describe airflow through a homogeneous isotropic soil medium and developed an expression for determining the shape factor. Liang et al. tested their new expression in the laboratory on repacked fine loamy sand in a metal soil container that was 30.5 cm in diameter and 34.3 cm high. They found that calculated k_a values were close to the actual measured values. The validity of the shape factor expression developed by Liang et al. has, however, not been tested for a range of soil types and soil horizons.

The objective of this study was to develop a portable air permeameter capable of measuring air permeability *in situ*, on-site (exhumed soil samples), and in the laboratory using two different sizes of core samples (100 cm^3 and 3140 cm^3). A second objective was to test the shape factor expression by Liang et al. (1995) under field conditions for different agricultural soils and to test scale dependency between the two measurement scales.

MATERIALS AND METHODS

Air Permeameter

The air permeameter was designed to measure k_a in an efficient and simple manner. The design of the instrument is based on earlier air permeameters used by Steinbrenner (1959), van Groenewoud (1968), Green and Fordham (1975), and Fish and Koppi (1994). The device is divided into six components as shown in Fig. 1:

1. A compressed-air cylinder with pressure regulator for an approximate control of pressure.
2. A two-stage regulator.
3. A bank of three precision flow meters covering different flow ranges (0. 2–2.3, 1.7–10.3, and 5.7–60 dm^3/min). Each of these is connected to a stopcock, allowing the air to flow exclusively in one of the flow meters.
4. A water manometer.
5. A soil core adaptor for large soil cores (20 cm diameter) and a soil core adaptor for small soil cores (6.1 cm diameter). The former includes an inflatable rubber tube, which is inflated by a simple foot pump to seal the adaptor inside the sample ring. The small soil core adaptor is sealed to the sample ring by pressing a flexible rubber O-ring upward in the sample holder. The soil core adaptor for large soil cores can be used for measurements both in the field and in the laboratory, whereas the adaptor for small soil cores is designed for use in the laboratory.

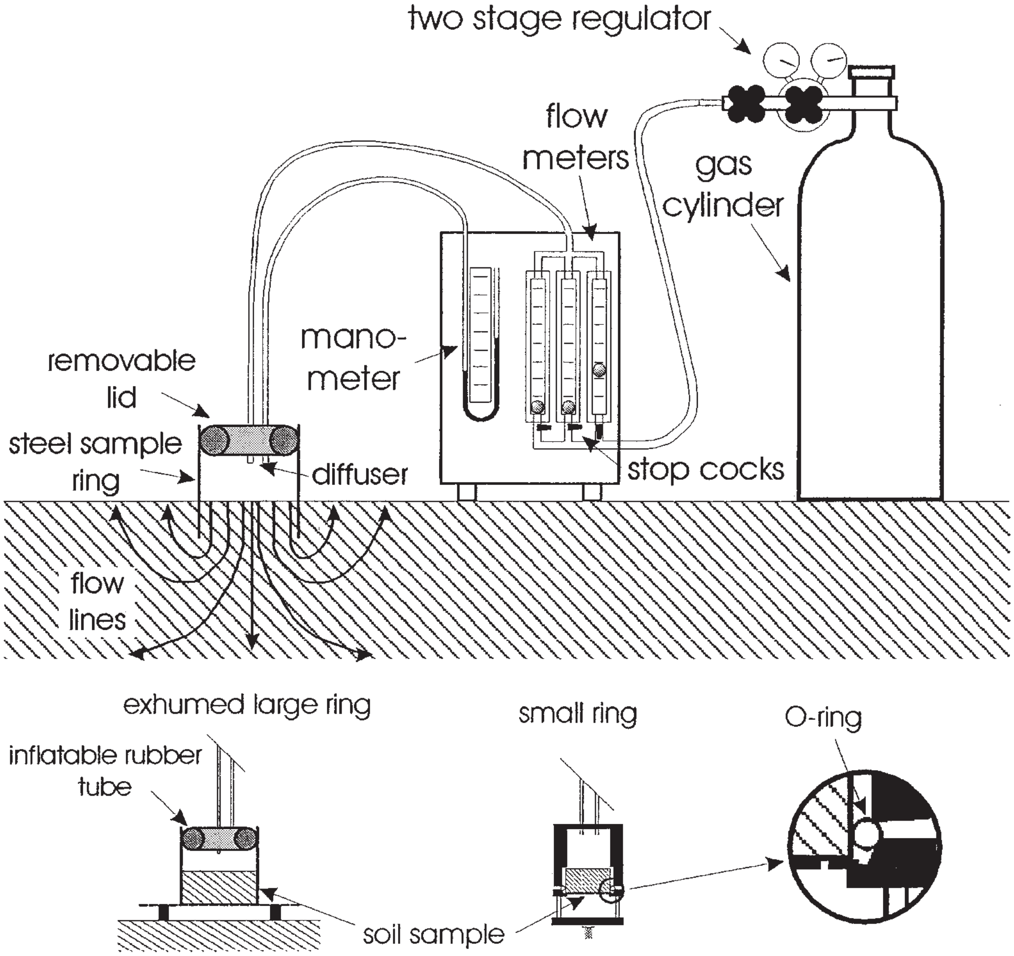

Fig. 1. Apparatus for measuring soil air permeability in situ, on-site, and in the laboratory using two ring sizes (100 cm^3 and 3140 cm^3).

6. Hoses linking the flow meter bank, the adaptor, and the manometer.

The air permeameter has several advantages compared with earlier air permeameters: (i) it can be used with two different sample sizes (100 cm^3 and 3140 cm^3); (ii) it is useable both in the field and in the laboratory; (iii) it is easily portable; (iv) it is inexpensive; (v) anyone can be trained to use it properly in a few minutes; and (vi) it is an instrument easily produced or repaired.

Soils Used

Measurements were carried out on six different Danish agricultural soils ranging from sand to clay loam. Physical properties of the soils are presented in Table 1.

Experiment A

The dependency of air permeability on sample size was initially tested in the laboratory on repacked soil samples using soil from the Foulum and Lundgård site (Table 1). Sieved and rewetted samples from each soil were packed to a height of 10 cm and a predefined bulk density in large steel cylinders with a 20-cm inner diameter. The two soils were packed at three different water contents, thereby yielding a total of six samples. Air permeability was measured on each soil sample using the permeameter described above. Three small soil samples using 100-cm^3 steel cylinders with a diameter of 6.1 cm were subsequently taken inside each large ring, and k_a was remeasured on these samples.

TABLE 1

Summary of sampling sites and physical properties of the studied soils

Site	Horizon	Depth (cm)	Org. matter	Clay <2 μm	Silt 2–20 μm	Fine sand 20–200 μm	Coarse sand 200–2000 μm	Soil type	Structure†	Bulk density (g cm^{-3})	Water content (m^3 m^{-3})
					(g 100 g^{-1})						
Lundgård	Ap		1.9	4.9	3.9	20.6	70.6	sand	‡	1.30	0.07–0.16
Foulum	Ap		2.5	9.0	10.1	36.4	44.5	loamy sand	‡	1.30	0.14–0.25
Fårdrup	Ap	0–33	2.5	15.3	13.3	47.1	21.9	sandy loam	weak/moderate coarse subangular	1.43	0.24
	Bvt	33–75	0.4	23.6	13.4	43.6	19.0	sandy clay loam	moderate coarse angular	1.58	0.24
Jyndevad	Ap	0–32	2.9	5.3	3.0	23.2	65.8	sand	very weak granular	1.44	0.12
	Bhs	32–45	1.6	5.1	1.9	16.7	74.8	sand	moderate weak subangular	1.43	0.12
Silstrup	Ap	0–31	3.1	24.2	15.2	36.4	22.3	sandy clay loam	moderate coarse/weak granular	1.41	0.28
	Bv	31–70	0.5	26.3	14.8	35.9	21.5	sandy clay loam	strong coarse angular/moderate coarse columnar	1.66	0.26
Slæggerup	Ap	0–26	2.0	21.0	18.3	42.9	15.7	sandy clay loam	coarse angular	1.56	0.31
	Bv/Bvt	26–42	0.9	18.2	15.2	46.5	19.2	sandy loam	moderate coarse angular/moderate very coarse subangular	1.60	0.28

†According to Soil Survey Division Staff (1993).

‡Sieved, packed soil was as used in the experiment.

Experiment B

Field measurements were carried out in the spring, summer, and autumn of 1999 at the Fårdrup, Jyndevad, Silstrup, and Slæggerup sites (Table 1). Each field was approximately 2 hectares in size. Measurements were carried out at three points in three different plots at each field site. At each point, k_a was measured in the Ap horizon (5–15 cm) and in the B horizon (approx. 35–45 cm) using the air permeameter. Before each measurement the soil surface was trimmed with a shovel, and a large ring was inserted 10 cm into the soil. To avoid lateral movement of the cylinder, a wooden guide was used to insure vertical insertion into the soil, as proposed by Liang et al. (1996). In order to minimize air flow between the soil and the cylinder wall, the soil was kneaded carefully using an 8-mm-wide plastic ring fitting exactly the inside border of the steel cylinder. After sealing the adaptor on to the cylinder, the *in situ* air permeability($k_{a,in\ situ}$) was measured. The soil sample was then exhumed carefully from the soil, the lower end was trimmed, and the soil sample was placed on a metal grid and the on-site air permeability ($k_{a,on\text{-}site}$) measured with well defined boundary conditions. Finally, three 100-cm^3 soil cores using the small rings were extracted from each large ring. The 100-cm^3 samples in the laboratory were weighed and air permeability($k_{a,lab}$) was measured using the soil core adaptor for the small rings. The soil samples (100 cm^3) were then oven dried at 105 °C for 24 h and weighed in order to determine soil bulk density and water content.

Calculations of Air Permeability and Shape Factor

The flow of gas through porous media is at a low pressure gradient comparable to water flow and follows Darcy's law,

$$q = \left(\frac{k_a}{\eta}\right)\left(\frac{dp}{dx}\right) \tag{1}$$

where q is the specific air flow rate [L T^{-1}], k_a is air permeability [L^2], p is the pressure [M L^{-1} T^{-2}], η is the dynamic gas viscosity [M L^{-1} T^{-1}] corrected for temperature, and x is distance (in flow direction) [L]. Air permeability of exhumed soil samples ($k_{a,on\text{-}site}$) and ($k_{a,lab}$) was calculated using an integration of Eq. (1) (Kirkham, 1947),

$$Q = \frac{k_a\,\Delta P a_s}{\eta L_s} \tag{2}$$

where Q is the volumetric flow rate [L^3 T^{-1}], ΔP is the pressure difference across the sample [M L^{-1} T^{-2}], a_s is the cross-sectional area [L^2], and L_s

is the length of the sample [L]. Air permeability for the *in situ* measurements ($k_{a,in\ situ}$) were calculated using a reorganization of Eq. (2), where the cross-sectional area and the length of the soil sample are replaced by the shape factor, A [L] (Grover, 1955),

$$q_v = \frac{k_a \Delta P A}{\eta} \tag{3}$$

The shape factor A may be regarded as an estimate of the a_s/L_s quotient in Eq. (2) in a measuring condition, where neither a_s nor L_s involved in the flow is well defined. The shape factor A in this work was determined using the finite element model (ANSYS F) developed by Liang et al. (1995). The shape factor equation of ANSYS F is,

$$A/D = 0.4862\,(D/L_s) - 0.0287\,(D/L_s)^2 - 0.1106 \tag{4}$$

where D is the inside diameter of the soil core.

Statistical Analysis

The significance of differences between $k_{a,in\ situ}$ and $k_{a,\text{on-site}}$ using the large samples was determined by paired *t*-test. The significance of differences between k_a measured on small and large repacked soil samples and the significance of differences between $k_{a,on\text{-}site}$ and $k_{a,lab}$ were tested using the likelihood ratio test. For the repacked soil samples, data were modeled as

$$y_{ikl} = \mu + location_i + water_k + \epsilon_{ikl} \tag{5}$$

where i is the number of locations, k is the number of different water contents, l is the number of measurement for each water content, y is the value of differences between the log-transformed values, μ is the mean of the differences between the log-transformed values, and ϵ is a residual error. For the $k_{a,on\text{-}site}$ and $k_{a,lab}$ measurements, data were modeled as,

$$y_{ijm} = \mu + \epsilon_{ijm} \tag{6}$$

where j is number of plots (three plots on each location), and m is number of points (three measurements in each plot). Because three small rings are sampled inside one large ring, the same large ring will occur in all three differences. Correlation structure was then compound symmetry between the differences (i.e., a common correlation between all three differences of the same large ring). The hypothesis for the three tests was that the mean of the differences was equal to zero.

RESULTS AND DISCUSSION

The measurements of k_a on small and large repacked samples obtained in experiment A are compared in Figure 2. As expected for these

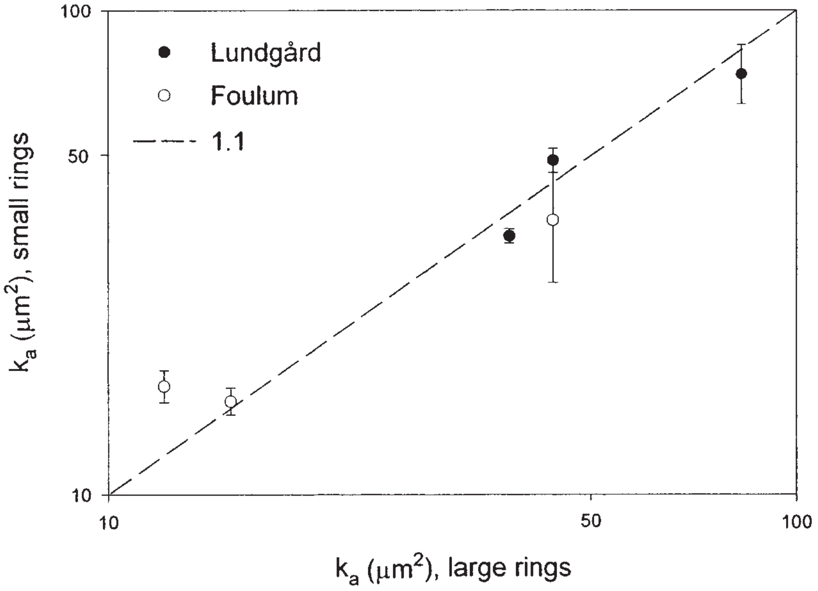

Fig. 2. Air permeability measured in the laboratory on repacked soil samples (100 cm^3 and 3140 cm^3) on two soil types. Error bars show ± one standard error (n=3).

homogenized samples there is a good 1:1 relationship between the k_a values obtained from the two sample types. The likelihood ratio test indicates as well that there is no significant difference between the two sample sizes (data not shown).

The results from experiment B include measurements *in situ* (large soil core in place), on-site (large exhumed soil core) and in the laboratory (exhumed small soil cores). The air permeability obtained in these three measuring situations are denoted $k_{a,in\ situ}$, $k_{a,on\text{-}site}$, and $k_{a,lab}$, respectively.

The relationships between $k_{a,in\ situ}$ and $k_{a,on\text{-}site}$ measured during experiment B are plotted in Fig. 3a and b for the A and B horizons, respectively. On-site and *in situ* measurements compared well, especially for the A horizon. *In situ* measurements at Silstrup (A and B horizon) and Slæggerup (B horizon) were slightly lower than the on-site values obtained under well defined boundary conditions (Table 2). Values of $k_{a,in\ situ}$ and $k_{a,on\text{-}site}$ from the more structured soils at Fårdrup, Silstrup, and Slæggerup generally compared less well than was the case for the less structured sandy soil at Jyndevad (Table 2). Values of $k_{a,in\ situ}$ in the B horizon at Fårdrup showed low variability compared with $k_{a,on\text{-}site}$ in the same horizon. This might be caused by dead-end macropores in the subsoils within the measured soil volume. Flow must occur from the macro-pores into the surrounding soil matrix. The presence of dead-end macropores, therefore, has only a weak influence on the *in situ* measurements, leading to low variability in k_a. When the soil sample was exhumed, some of these macropores became open-ended, and the variability increased as a result of direct piping. Bouma (1977) and Lauren et al. (1988) observed the same effect when measuring K_w *in situ* and on exhumed soil samples. A similar effect was observed by Mohanty et al. (1994), where K_w was highest when measured with a constant head laboratory permeameter in a comparative study with four *in situ* methods. Anderson and Bouma (1973) noted the same phenomenon using exhumed samples at different lengths.

The test of the finite element model of Liang

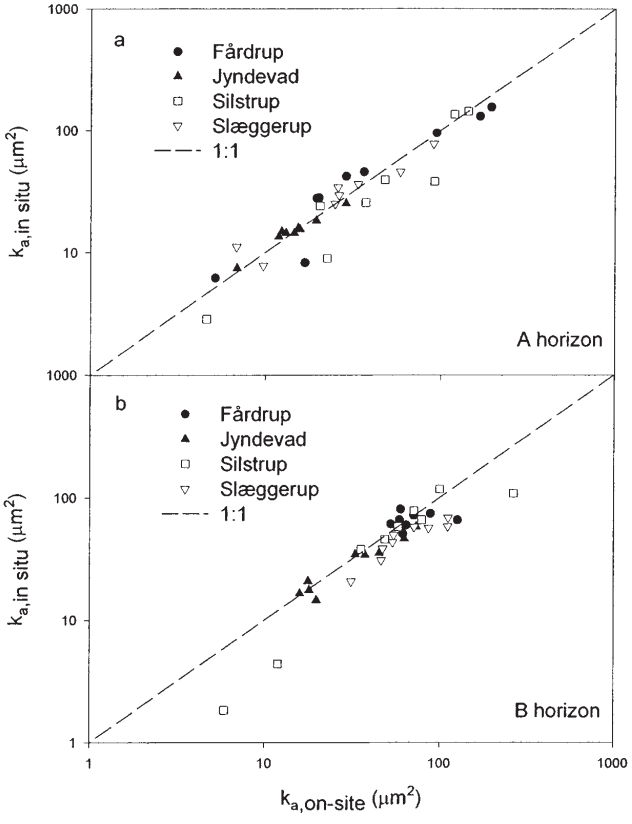

Fig. 3. Air permeability measured in situ ($k_{a,in\ situ}$) and on exhumed soil samples ($k_{a,on\ site}$) in the A and B horizon at four sites.

TABLE 2

Bias and test probabilities for air permeability measured in situ ($k_{a,in\ situ}$), on exhumed samples ($k_{a,on\text{-}site}$) and in the laboratory ($k_{a,lab}$) using 100 cm^3 samples

Site	Horizon	Bias ($k_{a,on\text{-}site}$ versus $k_{a,in\ situ}$)	P value (t–test)	Bias ($k_{a,on\text{-}site}$ versus $k_{a,lab}$)	P value (likelihood-ratio-test)
Fårdrup	Ap	0.013		−0.244	
	Bv	−0.028		−0.381	
Jyndevad	Ap	0.013		0.109	
	Bhs	−0.046		0.112	
Silstrup	Ap	−0.139		−0.370	
	Bv	−0.144		−0.750	
Slæggerup	Ap	0.017		−0.597	
	Bv/Bvt	−0.150		−0.464	
Total	Ap	−0.022	ns†	−0.254	0.0013
	B	−0.092	0.0304	−0.399	<0.0001

†Not significant.

et al. (1995) in this study was based on evaluating whether we obtained the same results with (on-site measurements) and without (*in situ* measurements using the shape factor) known boundary conditions at the lower end of the soil core. Thus the test of the differences between *in situ* and on-site measurements constitutes a test of the applicability of the shape factor. We note that Liang et al. carried out such experiments in the laboratory on disturbed soils, whereas we used undisturbed soils. Including all four sites, values of the *in situ* measurements in the A and B horizons were slightly underestimated compared with those obtained with well defined boundary conditions (Table 2). The *t*-test indicated that there was no significant difference between the measurement methods in the A horizon, but in the B horizon, a significant difference was detected ($P = 0.0304$). However, it should be noted that the three extreme observations (Fig. 3b) belong to one site (Silstrup). The results, therefore, indicate that the Liang et al. model may also be applied to structured soils in their undisturbed condition.

Figure 4a and b shows the result of corresponding $k_{a,on\text{-}site}$ and $k_{a,lab}$ measurements. The loamy soils (Fårdrup, Silstrup, and Slæggerup) using the small rings displayed a higher variability than the sandy and less structured soil at Jyndevad (Table 3). On the loamy soils, the geometric means of $k_{a,lab}$ were generally lower compared with $k_{a,on\text{-}site}$ (Table 2 and 3). For all data together (36 large and 108 small samples), the statistical tests indicated a significant difference between the two measurement methods in both horizons. These results are in accordance with the result from Garbesi et al. (1996), who investigated the effect of scale on k_a measured *in situ* using single-probe and dual-probe dynamic pressure techniques. They found that k_a increased with sampling scale, and their hypothesis was that preferential flow paths from plant root channels and animal burrows caused this scale dependence effect. When the sampling volume is increased, the greater is the likelihood of intercepting larger, faster flow paths and, as a result, a larger value of k_a. This was probably also the explanation for the more structured soils at Fårdrup, Silstrup, and Slæggerup (Table 1), some of them with a widely distributed network of earthworm burrows, showing an increasing value of k_a with increased scale. This effect was most pronounced for the B horizon, where the network of burrows was intact. In the disturbed and more homogenous Ap horizon, the scale dependence effect was less pronounced even though the majority of the data points were still found below the 1:1 line. In the sandy, less structured soil at Jyndevad, which did not show signs of macropores, there was no tendency toward sampling scale dependency (Fig. 4). Actually, the $k_{a,lab}$ values at Jyndevad were slightly higher compared with the $k_{a,on\text{-}site}$ values. Poulsen et al. (2001) observed the same similarity between permeability values measured on a weakly structured sandy loam using the same two sample sizes.

The variability in $k_{a,lab}$ within each set of three small rings was low for the unstructured Jyndevad soil, whereas for the more structured soils, the variability in $k_{a,lab}$ within each set of three small rings was high (Fig. 4). The different behavior in k_a for the two soil types illustrates the concept of a representative elementary volume (REV) of a soil representing the overall structure as derived from continuum theory (Bear, 1972). If the scale is increased, the measurement will be

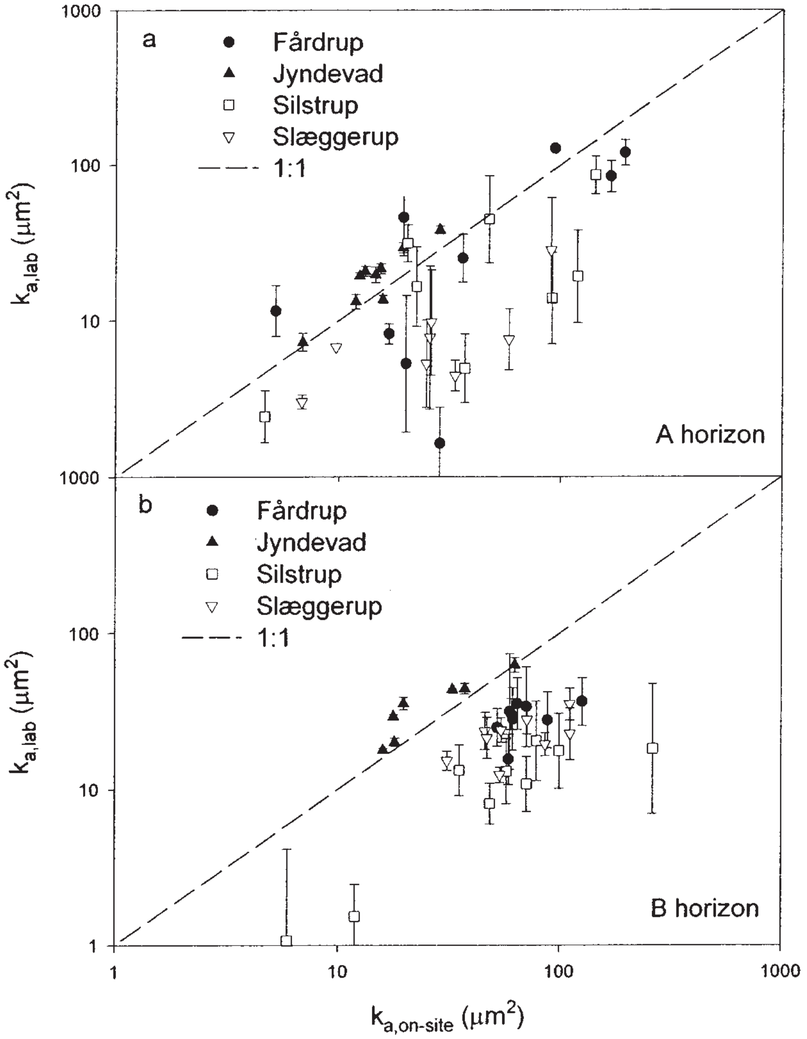

Fig. 4. Air permeability measured in the field on exhumed soil samples ($k_{a,on\ site}$) and in the laboratory on small exhumed soil samples ($k_{a,lab}$) in the A and B horizon at four sites. Values for $k_{a,lab}$ are geometric means (n=3). Error bars show ± one standard error.

TABLE 3

Mean air permeability ($k_{a,on\text{-}site}$ and $k_{a,lab}$) and range of ± one standard deviation (SD) at four locations

Site	Horizon	$k_{a,on\text{-}site}$ (μm²)†	SD (μm²)	$k_{a,lab}$ (μm²)†	SD (μm²)
		3140 cm³ samples		100 cm³ samples	
Fårdrup	Ap	36	(11–119)	19	(4–94)
	Bv	69	(53–90)	29	(14–59)
Jyndevad	Ap	14	(10–21)	18	(11–30)
	Bhs	26	(16–43)	34	(22–52)
Silstrup	Ap	39	(13–122)	17	(4–64)
	Bv	47	(15–145)	9	(3–33)
Slæggerup	Ap	26	(11–60)	8	(2–24)
	Bv/Bvt	63	(41–97)	22	(14–34)

†Values are geometric means.

an average of all the microscopic variations in a continuous assembly of voids. The minimum volume of a sample needed to obtain a consistent population of data is then defined as the REV. Different parameters may exhibit different spatial or temporal patterns, so that the REV for one parameter may differ from those for other parameters (Hillel, 1998). Kutílek and Nielsen (1994) stated that soils without structural development have a REV of about 100 cm^3 or less, whereas for a highly structured soil, the REV tends to be much higher. Both the large (3140 cm^3) and small (100 cm^3) sample volumes are probably above the representative elementary volume at Jyndevad, whereas the size of the small rings are apparently below the representative elementary volume in the structured soils at Fårdrup, Silstrup, and Slæggerup, leading to an increased variability in measurements. This variability stems from the presence of macropores in some small ring samples and no macropores in others. When sampling with the large rings, there is a greater likelihood that each sample contains at least one continuous macropore leading to a significant increase in k_a. This does not necessarily mean that the size of the large ring when sampling in the structured soil is above or at the REV, but the measurements illustrate the importance of using a large sample size in order to decrease the variability between measurements.

CONCLUSIONS

A portable air permeameter was developed to measure air permeability *in situ,* on-site, (exhumed soil samples) and in the laboratory using two different sizes of core samples. The newly developed device performed well, and it was possible to carry out reliable measurements in all three situations.

Results from this study show that it is possible to make reliable *in situ* air permeability measurements on both structured and unstructured soils using the shape factor model of Liang et al. (1995). A significant difference in air permeability measured on small (100 cm^3) and large (3140 cm^3) samples was found in both the A and the B horizons of four undisturbed soils. In addition, air permeability measured on exhumed small soil cores displayed higher variability for structured loamy soils compared with an unstructured sandy soil illustrating that the choice of an appropriate representative elementary volume (REV) is important for studies of air permeability.

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