Air Permeability in Undisturbed Volcanic Ash Soils: Predictive Model Test and Soil Structure Fingerprint

Per Moldrup,* Seiko Yoshikawa, Torben Olesen, Toshiko Komatsu, and Dennis E. Rolston

ABSTRACT

Soil air permeability (k_a) governs convective air and gas transport in soil. The increased use of soil venting systems during vadose zone remediation at polluted soil sites has created a renewed interest in k_a and its dependency on soil type and soil air-filled porosity (ε). Predictive $k_a(\varepsilon)$ models have only been tested within limited ranges of pore-size distribution and total porosity. Andisols (volcanic ash soils) exhibit unusually high porosities and water retention properties. In this study, measurements of $k_a(\varepsilon)$ on 16 undisturbed Andisols from three locations in Japan were carried out in the soil matric potential interval from −10 cm H_2O (near water saturation) to −15 000 cm H_2O (wilting point). Two simple power-function $k_a(\varepsilon)$ models, both with measured k_a at −100 cm H_2O as a reference point, gave similar and good predictions of $k_a(\varepsilon)$ between −10 and −1000 cm H_2O. For one location comprising finely textured and humic Andisols, both models largely underpredicted $k_a(\varepsilon)$ in dry soil (<−3000 cm H_2O), suggesting a sudden occurrence of highly connected air-filled pore networks during drainage. For the two other locations, the models satisfactorily predicted k_a also in dry soil. Using recently published data for gas diffusivity and soil-water retention together with the k_a data in the Millington and Quirk (1964) fluid flow model, a plot of equivalent pore diameter as a function of soil matric potential was made for each soil. This plot, labeled a soil structure fingerprint (SSF), proved useful for illustrating effects of soil cultivation and high organic matter content on soil structure.

Air permeability and its dependency on soil air-filled porosity (ε) and soil type govern convective air and gas transport in soil. Air permeability is an easily measured parameter both in situ, on-site (using exhumed soil samples), and in the laboratory using undisturbed or repacked soil samples (Kirkham, 1947; Iversen et al., 2001b; Poulsen et al., 2001). A k_a measurement at a given soil matric potential provides important information about the pore characteristics of the soil (Ball, 1981; Granovsky and McCoy, 1997; Schjønning et al., 2002), and the degree of soil structure and heterogeneity affecting fluid flow (Reeve, 1953; Kirkham et al., 1958; Moldrup et al., 2001).

Air and water permeability are closely linked (Corey, 1957), and valuable information about saturated and unsaturated hydraulic conductivity may be obtained from k_a measurements at given soil matric potentials (Aljibury and Evans, 1965; Ball et al., 1988; Blackwell et al., 1990). Recently, it was shown that k_a measured at a soil-water content close to natural field capacity (at −100 cm H_2O of soil matric potential) can be used to predict saturated hydraulic conductivity (Loll et al., 1999; Iversen et al., 2001a). This is useful, especially in large field scale studies where many point measurements are needed, since a measurement of k_a is easier and more rapid to perform and disturbs the soil less as compared with measuring water permeability.

Air permeability is also interesting in relation to greenhouse gas and soil remediation studies. Concerning greenhouse gas emissions, k_a may be a possible indicator for methane oxidation rates in surface soil (Ball et al., 1997). The increased use of soil venting (soil vapor extraction) during vadose zone remediation at soil sites contaminated with volatile and semivolatile organic chemicals has created a renewed interest in accurate $k_a(\varepsilon)$ predictive models, since air permeability typically will be the governing parameter for clean-up performance and efficiency (Poulsen et al., 1996, 1998). Ability to describe and predict k_a in undisturbed soils under varying soil moisture conditions is a prerequisite to improve soil venting system perfomance and clean-up efficiency at contaminated soil sites. It is therefore surprising that only a few measurements of k_a on undisturbed soil samples at different soil matric potentials are available in literature (Moldrup et al., 1998). Air permeability measurements on different soil types at different matric potentials and subsequent tests of predictive $k_a(\varepsilon)$ model against a larger k_a database are needed to evaluate the general applicability of $k_a(\varepsilon)$ models to describe and predict k_a in undisturbed soil (Moldrup et al., 2001).

An important challenge in soil physics is that most predictive models for transport parameters in the soil fluid phases have been tested only within limited ranges of soil pore-size distributions and total porosities (Moldrup et al., 2001). Volcanic ash soils (Andisols) exhibit pore-size properties that are very different from normal mineral soils, including larger total porosities and broader pore-size distributions. Data for Andisols are therefore valuable when testing the general validity of predictive models for the main gaseous and liquid phase transport parameters (the air and water permeabilities, and the gas and solute diffusion coefficients) in unsaturated soils. A companion study by Moldrup et al. (2003) supports the general validity of soil-water characteristic-based (SWC-based) models for the gas diffusion coefficient as a function of ε in undisturbed soil, by testing the SWC-dependent models against data for Andisols from three locations in Japan. This study will focus on the same in relation to the k_a.

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Abbreviations: RMSE, root mean square error; SWC, soil-water characteristic; SSF, soil structure fingerprint.

Andisols show a wide variation in soil texture, but exact particle-size distribution is difficult to determine since sand, silt, and clay contents do not have as precise a meaning for Andisols as for soils consisting largely of crystalline minerals (Warkentin and Maede, 1974; Shoji et al., 1993). Therefore, the physical characteristics of Andisols are better defined by their detailed SWC curve (pore-size distribution). Andisols exhibit a wide range of pore sizes that retain a large amount of water with varying matric potentials (Furuhata and Hayashi, 1980; Saigusa et al., 1987). Andisols typically have a well-developed and uniform (granular or blocky) soil structure with a small characteristic length (e.g., aggregate size). Therefore, relatively small sample sizes (down to 100 cm^3) can be used as representative elementary volume for undisturbed Andisols (Sato and Tokunaga, 1976; Miyazaki, 1993). A dominant constituent of many Andisols is Allophane, a highly porous mineral. The unusually high total porosity (between 0.6 and 0.85 cm^3 cm^{-3}) and content of micropores found in Andisols is mainly due to the intra- and interparticle pores of allophane. For more on the mineralogical, chemical, and physical characteristics of Andisols, we refer to Shoji et al. (1993), Iwata et al. (1995), and our companion paper (Moldrup et al., 2003).

This study is based on air permeability data measured on 16 Andisols from Japan. The measurements were done on undisturbed soil samples in a broad soil matric potential range between −10 (close to water saturation) and −15 000 cm H_2O (wilting point). The main objectives of this study were to (i) test the ability of recent air permeability models developed by Moldrup et al. (1998, 2001) and based on the Millington and Quirk (1960) or the Campbell (1974) pore distribution models to predict measured $k_a(\varepsilon)$ for the undisturbed Andisols, and (ii) combine detailed SWC data, gas diffusivity data, and air permeability data into a so-called SSF plot that may help illustrate effects of factors such as soil management and organic matter content on soil structure and pore continuity.

MATERIALS AND METHODS

Air permeability was measured on 100-cm^3 undisturbed soil samples drained to different soil matric potentials (ψ) using either a hanging water column ($\psi \geq -30$ cm H_2O) or a pressure plate apparatus ($\psi < -30$ cm H_2O). Air permeability was measured at 20°C by the steady-state method of Grover (1955) where air at a constant, small pressure difference flows through the soil column at a rate that is proportional to the air permeability. The experimental procedure used is described by Moldrup et al. (1998) and Schjønning et al. (1999) and includes careful kneading of the soil surface at the boundary to the metal ring housing the soil core, in order to minimize the risk of preferential air flow along the metal ring.

The measurements were conducted as part of a study to evaluate factors that influence plant disease and crop yield. Besides water retention, gas diffusivity, and total porosity, only limited information about the soils and their physical characteristics are available. Detailed soil texture data were not attempted measured as the soils were thought better characterized by the detailed pore-size distributions (SWC curves). Measurements of the SWC curve and the gas diffusivity as a function of soil-air content were carried out on the same soil samples and at the same soil-water matric potentials as used for the air permeability measurements. The SWC and gas diffusivity data are presented in the companion study by Moldrup et al. (2003).

An overview of the 16 Andisols is provided in Table 1, including soil type description and the soil-water content, relative gas diffusivity (D_P/D_0; the ratio of gas diffusion coefficients in soil and free air), and k_a at field capacity moisture content (−100 cm H_2O of matric potential). More detailed SWC data are provided in Table 1 of Moldrup et al. (2003). A brief description of the 16 Andisols and the $k_a(\varepsilon)$ data is given below. The same soil labeling (names) used by Moldrup et al. (2003) is adopted in this study (Table 1) to allow for a direct comparison of the data and figures in the two studies. The 16 soils are:

(i) Five Andisols from Tsumagoi, Gunma Prefecture, Honshu (mainland Japan), labeled Tsumagoi 3 to 7. Air permeability was measured on undisturbed soil samples at nine water potentials [pF = 1.0, 1.3, 1.5, 1.8, 2.0, 2.5, 3.0, 3.5, and 4.2, where pF = log (−ψ; the matric potential in cm H_2O)]. The sample area is characterized by humic and fine-textured Andisols with typically 30 to 50% clay, 25 to 40% silt, and 20 to 45% sand (predominantly fine sand). The main crop was

Table 1. Selected physical properties for 16 Andisols, including volumetric soil-water content, relative gas diffusivity (D_p/D_0), and air permeability (k_a) at −100 cm H_2O (pF 2) of soil matric potential.

Soil	Description†	Total Porosity	Soil water content at pF 2	D_p/D_0 at pF 2	k_a at pF 2
		m^3 m^{-3}			μm^2
Tsumagoi 3	H	0.770	0.428	0.103	90.9
Tsumagoi 4	Hc	0.726	0.511	0.031	11.2
Tsumagoi 5	Hc	0.732	0.611	0.008	1.77
Tsumagoi 6	SI	0.834	0.555	0.069	30.5
Tsumagoi 7	Fs	0.756	0.585	0.026	21.2
Miura 1	Lc	0.687	0.463	0.029	7.30
Miura 2	Lc	0.715	0.448	0.059	15.0
Miura 3	Lc	0.819	0.589	0.034	20.5
Miura 4	Lc	0.750	0.429	0.082	27.8
Miura 5	Lc	0.753	0.469	0.074	15.0
Kyushu 1	H	0.697	0.556	0.020	37.8
Kyushu 2	H	0.783	0.696	0.012	5.95
Kyushu 3	H	0.802	0.699	0.014	8.11
Kyushu 4		0.758	0.385	0.157	167.6
Kyushu 5		0.685	0.490	0.029	15.0
Kyushu 6		0.708	0.512	0.032	21.6

† Fs = floating stone layer; H = highly humic soil; Hc = highly humic clay soil; Lc = light clay soil; SI = silt loam.

cabbage. Tsumagoi 3 through 5 were sampled at the 0- to 5- (loamy soil), 20- to 25- (clayey soil), and 44- to 49-cm (clayey soil) depth at a highly humic (typically 9−11% organic C) cultivated field. Tsumagoi 6 and 7 were sampled at the 25- to 30- and 76- to 81-cm depth at a noncultivated field. Tsumagoi 7 had a visibly different soil structure including small (mm-size) porous stones, a phenomenon known as a *floating porous stone layer*. The Tsumagoi sampling area is further described by Osozawa et al. (1994).

(ii) Five Andisols from Miura, Kanagawa Prefecture, Honshu (mainland Japan), labeled Miura 1 to 5. Air permeability was measured on undisturbed soil samples at eight water potentials (pF = 1.0, 1.5, 1.8, 2.0, 2.5, 3.0, 3.5, and 4.2). The sample area is characterized as light-clay Andisols. The main crop was Japanese radish (*Raphanus sativus* L. var. *niger* J. Kern.). Miura 1 to 3 were sampled at the 0- to 5-, 30- to 35-, and 50- to 55-cm soil depth at a cultivated field (deep plow treatment). Miura 4 and 5 were sampled at the 0- to 5- and 30- to 35-cm depth at a cultivated field where a so-called exchange layer treatment (exchange of surface and subsurface soil) was carried out 3 to 4 yr before sampling.

(iii) Six Andisols from Kumamoto prefecture in Kuyshu (south Japan), labeled Kyushu 1 to 6. Air permeability was measured on undisturbed soil samples at six water potentials (pF = 1.0, 1.5, 2.0, 3.0, 3.5, and 4.2). The sample areas (grasslands) were characterized as humic and highly humic Andisols. Kyushu 1 to 3 were sampled at the 4- to 9-, 25- to 30-, and 45- to 50-cm depth at a highly humic field. Kyushu 4 to 6 were sampled at the 3- to 8-, 17- to 22-, and 45- to 50-cm depth at a humic field.

The data from this study hereby represent air permeability measurements on a larger number of undisturbed soils (16) at more soil matric potentials (6−9) than previously available in literature (cf. Moldrup et al., 1998, 2001), making the data set valuable for tests of predictive $k_a(\varepsilon)$ models.

Air Permeability Models

Moldrup et al. (1998) suggested that air permeability as a function of ε in undisturbed soils can be described by a simple power function,

$$k_a/k_a^* = (\varepsilon/\varepsilon^*)^{\eta}, \quad [1]$$

where ε is the volumetric soil-air content, k_a* and ε* are reference point values of air permeability and soil-air content at a given soil matric potential (ψ), and η is a tortuosity/connectivity parameter. Moldrup et al. (1998) found that setting η = 2, analogous to the tortuosity term by Millington and Quirk (1960) for fluid permeability and Buckingham (1904) for gas diffusivity, best described measured $k_a(\varepsilon)$ for 13 sandy and loamy soils. Other $k_a(\varepsilon)$ models based on the well known Millington and Quirk (1961) and Brooks and Corey (1966) tortuosity/connectivity functions showed less prediction accuracy (Moldrup et al., 1998).

However, the modified Millington and Quirk (1960) model (η = 2) largely overestimated measured $k_a(\varepsilon)$ data for a clay loam soil at three depths and representing two soil cultivation methods (total of six data sets) (Moldrup et al., 1998). Reexamining the model test of Moldrup et al. (1998), a likely reason for the model overprediction is that the reference point for the clay loam soil was taken at ψ = −1100 cm, that is, at relatively dry conditions where a sudden increase in $k_a(\varepsilon)$ was observed (Ball et al., 1988). The reference point in the study by Moldrup et al. (1998) was merely taken at the highest ε where measurements were available and therefore at different ψ values for each soil (between −100 and −3000 cm H_2O). This was necessary for lack of a common ψ value where k_a was measured for all soils considered.

Alternatively, the reference point can be taken at a fixed soil matric potential. Recent gas diffusivity models (Moldrup et al., 2000, 2003) use a reference point value at −100 cm H_2O, corresponding to a water content close to natural field capacity for most soils. Traditionally, the reference point is taken at drier soil conditions, mostly at soil-air saturation (zero moisture content). It appears more appropriate to select the reference point at the field capacity moisture content and not at air saturation for several reasons. First, it is easy, rapid, and nondestructive to drain an undisturbed soil sample to −100 cm H_2O of matric potential and measure k_a (Iversen et al, 2000a) while, in comparison, it is impossible to drain the soil of all its water without disturbing the soil structure. Second, an in situ measurement of k_a near field capacity (e.g., a few days after rainfall or irrigation) can directly be used in the $k_a(\varepsilon)$ model. Third, the value of k_a at −100 cm H_2O is closely linked to soil saturated hydraulic conductivity (Loll et al., 1999) making it possible to link predictive air and water permeability models. Fourth, this represents an important step towards unifying the predictive models for gas diffusivity and air permeability since both types of models will be based on the same reference point soil matric potential. Therefore, −100 cm H_2O is suggested as the reference point in Eq. [1], yielding

$$k_a/k_{a,100} = (\varepsilon/\varepsilon_{100})^{\eta}, \quad [2]$$

where $k_{a,100}$ and ε_{100} are the soil-air permeability and soil-air content at −100 cm H_2O of matric potential. Moldrup et al. (1998) suggested that η be taken as a function of the Campbell (1974) pore-size distribution index, b. The value of b corresponds to the slope of the SWC curve plotted in a Log(θ)-Log(−ψ) coordinate system, where θ is the volumetric soil-water content. Moldrup et al. (1998, 2001) found that the originally suggested expression for η (= 1 + 0.25b) failed to accurately describe the measured $k_a(\varepsilon)$ data for most soils considered. Moldrup et al. (2001) found that changing the expression to η = 1 + 0.05b well described measured $k_a(\varepsilon)$ data for six undisturbed soils representing a broad soil textural range (11 to 46% clay).

To compare air permeability models, the root mean square error (RMSE) of prediction was used for best overall fit compared with measured data,

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}, \quad [3]$$

where d_i is the difference between the predicted and the measured value of k_a at a given ε (i.e., at a given matric potential), and *n* is the number of measurements.

RESULTS AND DISCUSSION

The Campbell (1974) SWC model accurately described the measured data in the entire matric potential interval from −10 cm H_2O (pF 1) to −15 000 cm H_2O (pF 4.2) for all 16 Andisols. Figure 1 shows data and Campbell SWC model fit for four of the Andisols. For all 16 soils, the coefficient of linear regression, r^2, in a Log(θ)-Log(−ψ) plot was generally >0.99, and values of b ranged between 8.3 (Miura 2) and 40.8 (Kyushu 2). Due to the higher water holding ability and broader pore-size distribution of the Andisols compared with normal mineral soils, the simple (power function based) Campbell SWC model is able to fit the measured SWC

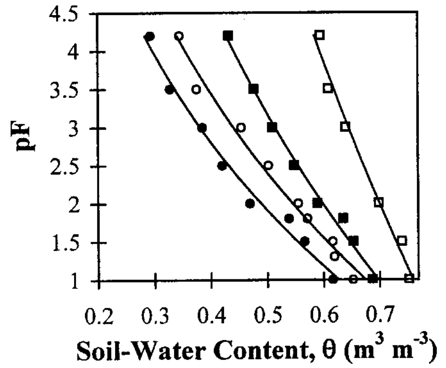

Fig. 1. The Campbell (1974) soil-water characteristic model (solid lines) fitted to measured data for four Andisols. The pF equals Log($-\psi$ in cm H_2O). Data from Moldrup et al. (2003).

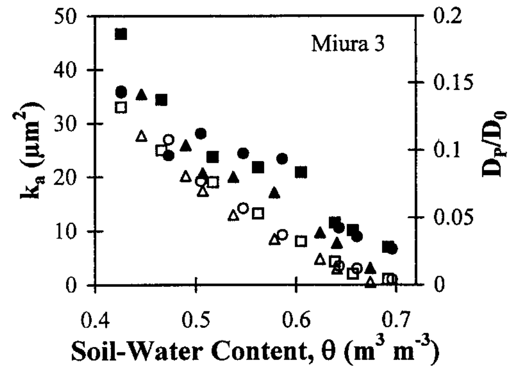

Fig. 2. Air permeability (closed symbols; data from this study) and gas diffusivity (open symbols; data from Moldrup et al. (2003) as functions of volumetric soil-water content for Miura 3 Andisol. D_P and D_0 are the gas diffusivities in soil and free air, respectively. Measurements on three closely spaced 100-cm^3 undisturbed soil cores are shown.

data within a much broader ψ interval than for normal mineral soils. See Moldrup et al. (2003) for further presentation and discussion of the SWC data and the capability of the Campbell SWC model to accurately describe the data.

The local-scale variability in k_a, measured on typically three closely spaced (within a 0.1-m^2 area) 100-cm^3 soil cores, was relatively low compared with other air permeability studies on normal mineral soils (e.g., Schjønning et al., 1999; Iversen et al., 2001a,b). As expected, the variability in k_a was higher than for gas diffusivity when measured on the same soil cores, with a typical example shown in Fig. 2. Thus, soil structure clearly has a more pronounced effect on air permeability compared with gas diffusivity, as also shown and discussed for normal mineral soils by Moldrup et al. (2001). Still, the relatively small local-scale variability suggests that 100 cm^3 is a sufficient sample size for the Andisols that typically exhibit a well-developed and uniform soil structure. This is in agreement with the observations and suggestions by Sato and Tokunaga (1976), and the discussion in Moldrup et al. (2003) regarding the gas diffusivity data for the 16 Andisols.

Figure 3 shows measured $k_a(\varepsilon)$ data for 12 of the 16 soils, and model predictions by Eq. [2] with $\eta = 2$ and $\eta = 1 + 0.05b$, respectively. Data are presented as the mean of typically three measurements (on three closely spaced soil cores) at each matric potential. Local-scale variability in k_a was generally low and comparable with the variability for the Miura 3 soil in Fig. 2. It appears that both models ($\eta = 2$ and $\eta = 1 + 0.05$ b) satisfactorily predict $k_a(\varepsilon)$ for the Kyushu soils across the entire soil-air content range. The data for the Miura soils are also well predicted, especially at lower soil-air contents (except for Miura 4, mainly due to deviating measurements for one out of three soil cores). However, both $k_a(\varepsilon)$ models largely underpredict air permeability at higher soil-air contents for the Tsumagoi soils, corresponding to dryer soil conditions than pF 3. The four soils not shown in Fig. 3 exhibited the same trends as the 12 shown.

For the Tsumagoi 3 to 6 soils, a rapid increase in air permeability is observed around pF 3, suggesting that a highly-connected pore network is created in these clayey and humic Andisols when drained to around pF 3. Plotting the $k_a(\varepsilon)$ data in a Log(ε)-Log(k_a) coordinate system revealed two distinctively different slopes for $k_a(\varepsilon)$ data below and above pF 3, with a factor 3−5 higher value of slope in the low soil moisture range (pF > 3). This phenomenon cannot be captured by a simple power-function $k_a(\varepsilon)$ model so a more complex model, for example, a dual-porosity/dual-region model, is needed. The phenomenon is not reflected in the SWC curves for the Tsumagoi soils, which closely follow the simple Campbell (1974) single power function SWC model across the entire matric potential range from pF 1 to 4.2 (Fig. 1; Moldrup et al., 2003).

The sudden increase in k_a around pF 3 is also not apparent in the gas diffusivity (D_P/D_0) data for the Tsumagoi soils, as illustrated in Fig. 4 for Tsumagoi 6 (based on individual measurements on three closely-sampled soil cores). The deviation between the three individual measurements of air permeability or gas diffusivity at a given matric potential was very small for this soil. The air permeability, but not the gas diffusivity, exhibits a definite increase around pF 3 for all individual soil samples (Fig. 4). Generally, for all Tsumagoi soils, the gas diffusivity as a function of soil-air content was well predicted by simple, Campbell SWC-based prediction models (Moldrup et al., 2003) while similar models for air permeability could not predict $k_a(\varepsilon)$ for Tsumagoi 3 to 6 (Fig. 3). This documents that while gas diffusivity is mainly governed by air-filled pore space and pore-size distribution, air permeability is to a higher degree governed by soil structure (pore connectivity and continuity). Thus, the sudden increase in air permeability for the Tsumagoi soils cannot be described merely using a SWC-dependent model; some novel structural parameters are needed, especially in the low soil moisture range.

As drying to low soil matric potential makes volcanic ash soils less dispersible through irreversible aggregation (Kubota, 1976), the sudden increase in air permeability at pF 3 is not likely to be caused by collapse of the soil structure. In support of this, the increase in k_a was observed for all Tsumagoi soils and soil samples while soil-water retention and gas diffusivity did not show any signs of dramatic changes in the low moisture range.

A similar sudden increase in air permeability around pF 3 was observed for a cultivated clay loam soil (Ball et al., 1988), both in the case of direct drilling and plowing treatments and at three different depths. Thus, some finely textured and well-structured soils, both normal mineral soils and Andisols, can suddenly develop a highly connected pore network under dry conditions. It is noted that for Tsumagoi 7, the increase in k_a at pF 3 is less pronounced and the Moldrup et al. (2001) model ($\eta = 1 + 0.05b$) is able to reasonably well predict the measured $k_a(\varepsilon)$ data in both wet and dry soil (Fig. 3). This may partially be due to the small microporous stones observed in the Tsumagoi 7 soil, preventing the sudden increase in pore connectivity that was observed for the other Tsumagoi soils.

Figure 5 shows the test of all three $k_a(\varepsilon)$ models considered (Eq. [2] with $n = 2$, $1 + 0.05b$, and $1 + 0.25b$,

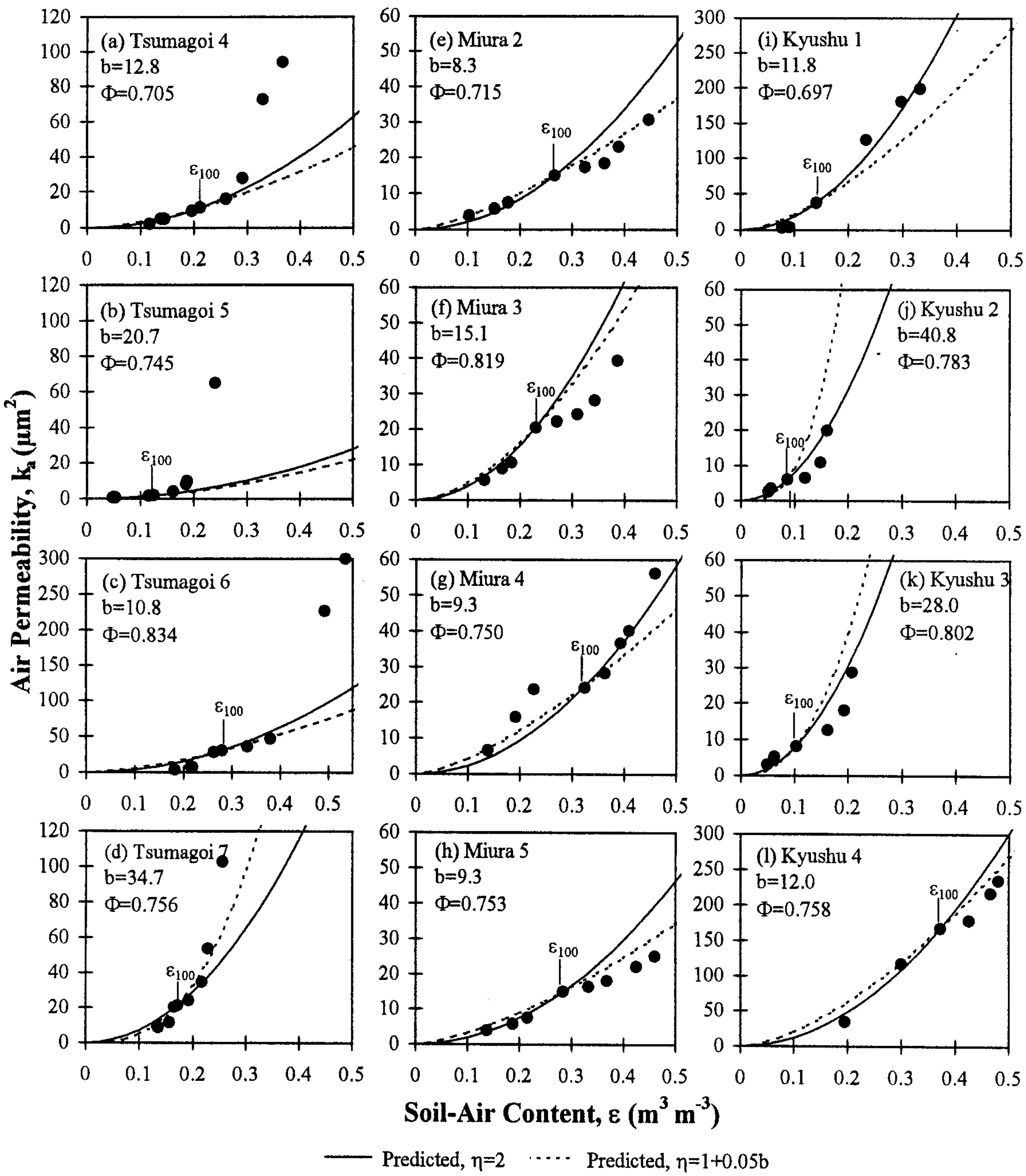

Fig. 3. Test of air permeability models, Eq. [2] with $\eta = 2$ and $\eta = 1 + 0.05b$, against measured data for 12 undisturbed Andisols. Values of Campbell b and total porosity (Φ) are given for each soil. Soil macroporosity (ε_{100}) is marked for each soil. Measurements are mean of three closely spaced soil cores. Note that three different y-scales are used (60, 120, and 300 μm^2).

respectively) against the measured data for all 16 Andisols (based on mean k_a values). Model performance is evaluated based on RMSE of prediction (Eq. [3]) in the wet (pF 1–3) and dry (pF > 3) matric potential ranges, and RMSE values are given in Fig. 5. In the matric potential interval from pF 1 to 3, both the soil type independent model ($\eta = 2$) and the Moldrup et al. (2001) model ($\eta = 1 + 0.05b$) perform satisfactorily. The width of the prediction interval is smaller than one order of magnitude and no tendency for a general over- or underestimation (bias close to zero for both models) was observed. However, for drier soil (pF > 3.5, i.e. $\psi < -3000$ cm H_2O) a large underprediction is evident for four of the five Tsumagoi soils (Fig. 3). The original model by Moldrup et al. (1998) ($\eta = 1 + 0.25b$) did not predict the measured $k_a(\varepsilon)$ data well, neither in wet nor dry soil, in agreement with observations by Moldrup et al. (2001) for six soils representing clay contents from 11–46%. Overall, comparing the results of Moldrup et al. (2001) and this study, it is encouraging that the simple, power-function based models (Eq. [2] with $\eta = 2$ or $\eta = 1 + 0.05b$) seem able to well describe air permeability in the matric potential range where $k_a(\varepsilon)$ models would normally be applied, for example in relation to soil vapor extraction based subsurface remediation systems. The SWC-dependent model ($\eta = 1 + 0.05b$) did a better job overall for the 16 Andisols in this study and the six differently textured mineral soils in Moldrup et al. (2001). If the SWC (Campbell b) is not known, the modified Millington and Quirk (1960) model ($\eta = 2$) can be used instead and will typically perform almost as well. Both models require a reference point measurement of k_a at around -100 cm H_2O of matric potential.

Moldrup et al. (2000, 2001) showed that the gas diffusion coefficient at -100 cm H_2O can be accurately predicted from the soil-air content at -100 cm H_2O (ε_{100}, labeled the macroporosity and corresponding to the volumetric content of pores with a pore diameter > 30 μm). The same is not equally feasible for k_a due to the dominating effects of soil structure on air permeability. This is illustrated in Fig. 6, showing measured $k_{a,100}$ as a function of ε_{100} for the 16 Andisols. The three highly humic Kyushu soils are placed well above the other data

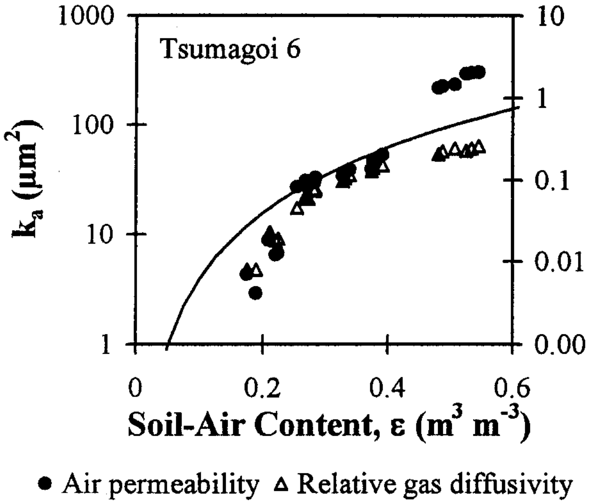

Fig. 4. Comparison of air permeability (k_a) and relative gas diffusivity (D_P/D_0) as a function of soil-air content (ε) for the Tsumagoi 6 Andisol. Measurements on three closely spaced soil cores. The solid line is a predictive model with reference-point at -100 cm H_2O of matric potential and with $\eta = 2$.

(open triangles at ε_{100} around 0.1 m^3 m^{-3} on Fig. 6). The rest of these data may appear to follow a reasonable linear relationship in the log($k_{a,100}$) vs. ε_{100} plot but looking at the individual locations, only the data for the Tsumagoi soils support such a relationship (best-fit line on Fig. 6). In contrast to the case for gas diffusivity, the available k_a data at present do not warrant the development of a predictive $k_{a,100}(\varepsilon_{100})$ model.

In conclusion, both comprehensive $k_a(\varepsilon)$ data for different soil types and identification of proper soil structural parameters governing air permeability in undisturbed soil are lacking. Therefore, a high model prediction accuracy as lately obtained for gas diffusivity (Moldrup et al., 2000, 2001, 2003) cannot be expected for $k_a(\varepsilon)$ in the near future, and a reference-point measurement of air permeability (e.g., close to field capacity water content) is therefore needed to obtain a reasonable $k_a(\varepsilon)$ prediction accuracy. As air permeability is easy and rapid to measure compared with gas diffusivity, more

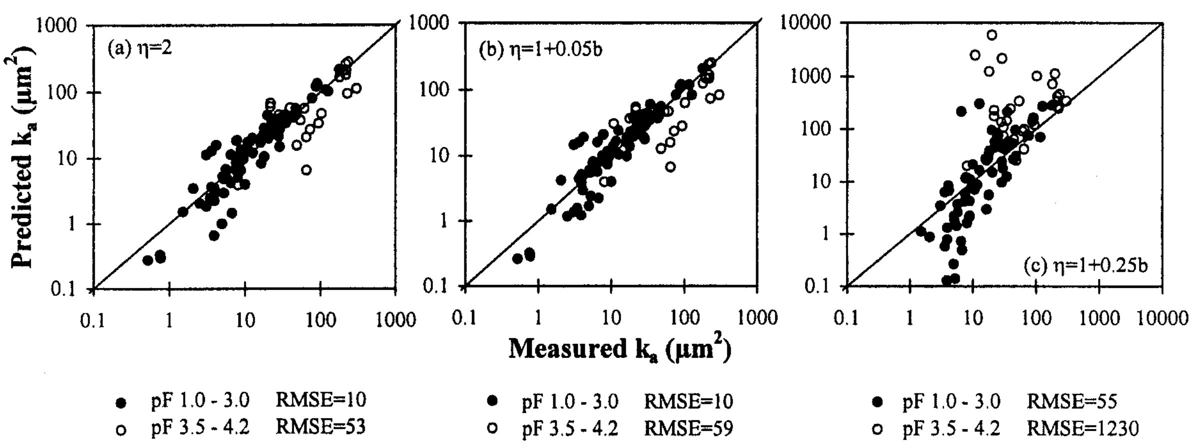

Fig. 5. Scatter plot comparison of predicted and measured air permeabilities in 16 undisturbed Andisols. Test of (a) Eq. [2] with $\eta = 2$, (b) Eq. [2] with $\eta = 1 + 0.05b$, and (c) Eq. [2] with $\eta = 1 + 0.25b$.

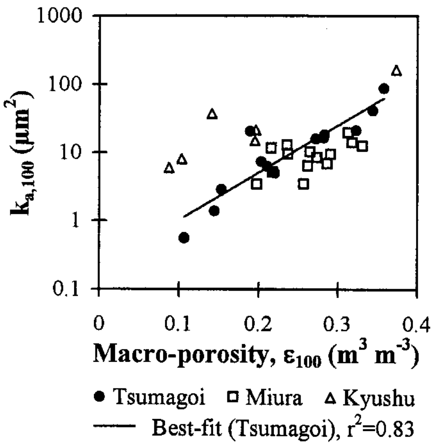

Fig. 6. Air permeability at −100 cm H_2O of soil matric potential ($k_{a,100}$) as a function of soil macroporosity (ε_{100}). Solid line is best-fit line to measured data for the Tsumagoi soils.

studies could easily be carried out to add to our understanding of the mechanisms affecting air permeability.

Soil Structure Fingerprint

Moldrup et al. (2003) combined the measurements of gas diffusivity and SWC at different matric potentials to suggest a plot showing incremental changes in gas diffusivity as a function of pF. This could be used to clearly distinguish between soils with high and low aeration potential, discussed in relation to plant diseases caused by poor soil aeration. As air permeability is a better indicator for soil structure than gas diffusivity (Moldrup et al., 2001), the combined use of air permeability, gas diffusivity, and SWC measurements at the same matric potentials should allow for a further characterization of soil structure. Millington and Quirk (1964) derived the following model to link air permeability and gas diffusivity, by combining Fick's law for diffusive transport with Poiseuille's law for convective fluid transport, and assuming soil pores to be uniform, tortuous, and nonjointed tubes of similar diameter,

$$d = 2\ [8k_a/(D_P/D_0)]^{0.5}, \qquad [4]$$

where d is the equivalent tube/pore diameter, D_P is the gas diffusion coefficient in soil, and D_0 is the gas diffusion coefficient in free air. Ball (1981) independently derived the same model and extended it to consider a porous medium with pores being jointed tubes of different diameter. The detailed air permeability, gas diffusivity, and SWC measurements on the same soil cores for the 16 Andisols allows a plot of d (Eq. [4]) as function of matric potential (pF). This plot is labeled a SSF.

Examples of SSF for six of the Andisols are shown in Fig. 7. In Fig. 7a, two Tsumagoi soils imply a more pronounced soil structure (pores with higher d) for the noncultivated compared with the cultivated (plowed) andisol, and a sudden increase in pore connectivity (increase in d) at pF ≥ 3. It appears that the smaller pores that are drained around pF 3 are linked with the larger pores and create a highly connected and continuous pore network.

Contrary to the behavior of the Tsumagoi soils, the two Miura soils depicted in Fig. 7b show a drop in d when the soil is dryer than pF 2, suggesting that the smaller pores that are drained above pF 2 reduce the continuity of the pore network and creates very tortuous or dead-end pore spaces. In agreement with the gas diffusivity analysis of Moldrup et al. (2003), no significant difference between the two cultivation methods is observed. For the humic Kyushu grassland soils (Fig. 7c), the structure is generally more pronounced than for the other soils (higher d values) within the whole matric potential interval, and the high humus content in Kyushu 1 facilitates high pore continuity at all matric potentials. It is noted that d could not be calculated for Kyushu 1 at pF 1 (gas diffusivity almost equal to zero) and for Kyushu 4 at pF 4.2 (gas diffusivity not measured).

In the study of Moldrup et al. (2001), d was calculated at pF 2 for six mineral soils (11–46% clay) for sieved soil, for structurally disturbed soil (repacked soil that was allowed to develop soil structure for 17 mo), and for undisturbed soil samples. The d values calculated at pF 2 for the Andisols in this study (d = 50 − 200 μm) are closest to the d values obtained for the structurally disturbed mineral soil from Moldrup et al. (2001) (d = 100 −250 μm). This is in agreement with the observation

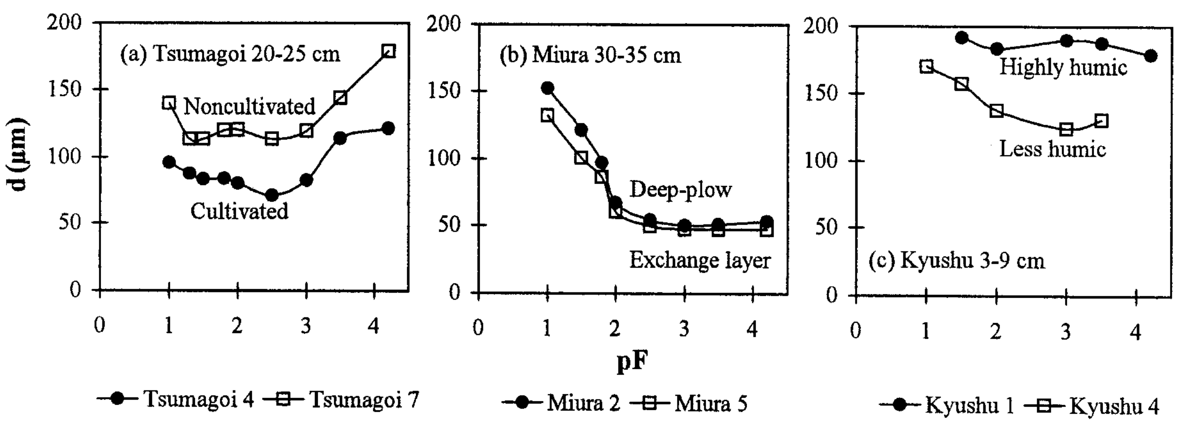

Fig. 7. Soil structure fingerprint (SSF) for 6 Andisols from (a) Tsumagoi, (b) Miura, and (c) Kyushu. The equivalent pore diameter, d, is calculated from measured air permeabilities and gas diffusivities (Eq. [4]).

that Andisols typically have a well developed and well distributed soil structure, mostly resembling a 'new' soil structure without the continuous macropores, cracks, or fissures that will cause much higher d values (Moldrup et al., 2001). If detailed measurements of air permeability, gas diffusivity, and SWC on the same, undisturbed soil cores are available, the proposed SSF type of plot (Fig. 7) appears useful to help evaluating differences in soil structure (pore network connectivity and continuity) for undisturbed soils.

CONCLUSIONS

Simple power function models for air permeability as a function of soil air content, with measured k_a at -100 cm H_2O used as reference point in the models, well predicted measured $k_a(\varepsilon)$ data for 16 Andisols between -10 and -1000 cm H_2O of matric potential, the range most relevant for soil-vapor extraction system design where air permeability will be a governing parameter for gas transport and fate. For some cases, $k_a(\varepsilon)$ in drier soil ($\psi < -3000$ cm H_2O) was underpredicted, due to a sudden increase in pore connectivity that was not observed from the gas diffusivity data and could not be explained from the SWC data.

Among the tested models, the SWC based $k_a(\varepsilon)$ model by Moldrup et al. (2001), Eq. [2] with $\eta = 1 + 0.05b$, is recommended. However, a soil type independent $k_a(\varepsilon)$ model based on the Millington and Quirk (1960) tortuosity term ($\eta = 2$) provided almost as accurate predictions. The present data did not support the development of a predictive model for reference point air permeability ($k_{a,100}$ in Eq. [2]) and, thus, a reference point measurement of k_a at or around the field capacity water content is needed in order to apply the $k_a(\varepsilon)$ models. Dual- or multiregion $k_a(\varepsilon)$ models that take into account soil structural effects in the dry moisture range would be valuable to develop when more data are available.

Combining detailed air permeability, gas diffusivity, and water retention data allows for a so-called SSF plot, depicting the equivalent pore diameter from the Millington and Quirk (1964)/Ball (1981) fluid flow model as a function of soil matric potential (pF). The SSF may help in analyzing soil type and soil management effects on soil structure and pore connectivity.

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