

## Modelling soil anaerobiosis from water retention characteristics and soil respiration

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### Abstract

Oxygen is a prerequisite for some and an inhibitor to other microbial functions in soils, hence the temporal and spatial distribution of oxygen within the soil matrix is crucial in soil biogeochemistry and soil biology. Various attempts have been made to model the anaerobic fraction of the soil volume as a function of structure, moisture content and oxygen consumption. Aggregate models are attractive but difficult to parameterize and not applicable to non-aggregated soils. Pore models are preferable for pragmatic reasons, but the existing versions appear to overestimate the anaerobic volume at intermediate soil moisture contents. A modified pore model is proposed, in which anaerobiosis is calculated from a range of air filled pore size classes, based on the soil water retention curve and the soil moisture content. In comparison with previous pore models which are based on the estimation of an average size of the air filled pores, the pore class model presented here appears to give more adequate estimates of anaerobic volumes, especially at intermediate moisture contents. The pore model is attractive for process modelling of anaerobic functions such as denitrification, since it can easily be parameterized by the water retention characteristics of a soil.

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**Keywords:** Anaerobiosis; Pore model; Soil moisture; Water retention curve

### 1. Introduction

Oxygen plays a key role in the metabolism of most microorganisms in soils: as a terminal electron acceptor in respiration, as a substrate for oxygenases, and as a toxic compound. As a result, many ecological functions in soils depend on the presence of free oxygen around the active cells. Well-known examples are the oxidation of ammonia (Wood, 1986) and methane (Hanson and Hanson, 1996), the primary cleavage of various aromatic compounds (Nojiri et al., 2001) and oxidative dehalogenation (Fetzner, 1998). Other metabolic functions, such as denitrification, methanogenesis and reductive dehalogenation (Fetzner, 1998), will only take place in the absence of oxygen. Well-drained soils are known to harbour both oxygenated and anoxic microsites, evidenced by the concomitant occur-

rence of both nitrification and denitrification (Firestone and Davidson, 1989). A thorough understanding of the dynamics of oxygen in soils is needed to enhance our understanding of process controls. Further, simulation models for any oxygen-sensitive process rely heavily on adequate simulations of oxygen concentrations in the soil matrix and its variations in time and space. In this study, we explore the possibilities of describing the anaerobic volume of soils as a function of oxygen consumption, water content and soil pore size distributions as derived from water retention characteristics.

The oxygen concentration in the soil water is primarily determined by two processes: the consumption of oxygen by respiration (from both roots and microorganisms) and the transport of oxygen by diffusion (Leffelaar, 1979; Arah and Vinten, 1995). The simplest formulation for respiratory oxygen consumption, which is applicable for larger scale modelling is a zero-order approach. According to Rappoldt and Crawford (1999), this is a satisfactory

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description for exploring the behaviour of soil structure models with respect to soil aeration. Diffusion can be described by Fick's law and can be related to e.g. the air-filled porosity or the relative soil moisture content.

This approach was used in a wide range of models for anaerobiosis in soils. Li et al. (2000) use soil field capacity as a substitute for effective soil porosity, and calculate the oxygen partial pressure in a given soil layer numerically from Fick's diffusion and soil respiration. However, the anaerobic fraction of a soil thus becomes a linear function of oxygen partial pressure, which unequivocally is not the case in structured soils (Leffelaar, 1979; Smith, 1980; Arah and Vinten, 1995). More complex descriptions try to model soil structure explicitly, in order to account for the effects of structural heterogeneity on the oxygen status. Several attempts have been made to find simplified representations of soil structure. Leffelaar (1979) and Smith (1980) model soil structure on the basis of spherical aggregates. The aggregates are assumed to be distributed log-normally (Smith, 1980) or packed hexagonally (Leffelaar, 1979). Van Veen (1977), Arah and Vinten (1995) and Groenendijk and Kroes (1999) model soil structure on the basis of parallel, cylindrical pores that are distributed in the soil matrix. Rappoldt and Crawford (1999) model a three-dimensional

fractal structure of air-filled pores in soil. The fractal model, resulting in irregularly shaped particles and pores, seems to give the most proper representation of soil structure. However, due to its high degree of discretization, the model is difficult to parameterize and can deal only with a limited number of soil moisture content levels.

Aggregate models give an explicit, although simplified, representation of the arrangement of soil particles. An advantage of this approach is that inter-aggregate and intra-aggregate pores (macropores and micropores) can be distinguished, which enables to model macroscale and microscale processes distinctively. However, for soils that do not consist of aggregates, e.g. peat soils or single-grained sandy soils, they will be useless. Pore models, in contrast, are generally applicable to all soil types and can be readily parameterized from water retention characteristics. This makes pore models preferable tools in process studies as well as in dynamic modelling of oxygen-sensitive biological processes (e.g. denitrification, methanogenesis).

A common feature of existing pore models (Van Veen, 1977; Arah and Vinten, 1995; Groenendijk and Kroes, 1999) is that the distribution of air-filled pores is assumed to be properly represented by a 'typical' average pore size which is used to calculate anaerobiosis. The aim of this

Table 1  
Parameters used for comparison of the two models

Symbol	Description	Value
$\sigma$	Surface tension of water	$73 \times 10^{-3} \text{ N m}^{-1\text{a}}$
$\rho$	Density of water	$1 \times 10^3 \text{ kg m}^{-3}$
$g$	Gravitational constant	$9.8 \text{ m s}^{-2}$
$Q$	Oxygen consumption rate in aerobic zone	$30 \times 10^{-6} \text{ mol O}_2 \text{ m}^{-3} \text{ s}^{-1\text{b}}$
$D_w$	Diffusion coefficient of $\text{O}_2$ in water	$1.5 \times 10^{-9} \text{ m}^2 \text{ s}^{-1\text{a}}$
$\tau$	Tortuosity	$1.5^{\text{a}}$
$\alpha_w$	Solubility of $\text{O}_2$ in water relative to solubility in air	$0.03 (\text{m}^3 \text{O}_2 \text{ m}^{-3} \text{H}_2\text{O})/(\text{m}^3 \text{O}_2 \text{ m}^{-3} \text{soil})^{-1\text{a}}$

<sup>a</sup>Arah and Vinten (1995).

<sup>b</sup>Leffelaar (1979); Langeveld and Leffelaar (2002).

Table 2  
Van Genuchten parameters for a selection of Dutch topsoils (data are derived from Wösten et al., 1994) and for the sorption and desorption curves for hysteresis (data are derived from Korzilius, 1989).

Soil code	Description	$\theta_r$ ( $\text{m}^3 \text{H}_2\text{O m}^{-3}$ soil)	$\theta_s$ ( $\text{m}^3 \text{H}_2\text{O m}^{-3}$ soil)	$\alpha$ ( $\text{m}^{-1}$ )	$n$ (dimensionless)
B2 <sup>a</sup>	Slightly loamy, fine to moderate fine sand	0.02	0.43	2.27	1.548
B8 <sup>a</sup>	Moderate light silt	0.00	0.43	0.96	1.284
B11 <sup>a</sup>	Moderate heavy clay	0.00	0.60	2.43	1.111
B14 <sup>a</sup>	Silty loam	0.01	0.42	0.51	1.305
B17 <sup>a</sup>	Peaty clay	0.00	0.72	1.80	1.140
Herveld <sup>b</sup>	Loam, sorption	0.005	0.48	2.702	1.21790
Herveld <sup>b</sup>	Loam, desorption	0.005	0.48	2.692	1.35341
Lelystad <sup>b</sup>	Sandy loam, sorption	0.08	0.48	1.983	1.54240
Lelystad <sup>b</sup>	Sandy loam, desorption	0.08	0.48	2.377	1.92083
Sevenum <sup>b</sup>	Loamy fine sand, sorption	0.06	0.488	1.131	1.78534
Sevenum <sup>b</sup>	Loamy fine sand, desorption	0.06	0.488	3.419	2.21238

<sup>a</sup>Soil code as used in Wösten et al. (1994).

<sup>b</sup>Soil name (location) as used in Korzilius (1989).

study is to test this assumption and to explore the possibilities of using the pore size distribution as derived from the water retention curve in order to improve the prediction of anaerobiosis in soils.

**2. Methods**

*2.1. Modelling soil structure*

Soil structure is by definition the arrangement of primary soil particles into secondary particles, peds. Instead of describing the distribution of peds, as in the aggregate models, an alternative is to estimate the pore size distribution of the soil. The distribution of pore sizes determines the water retention characteristics of a soil. It

can be deduced from the water retention curve, which gives the relation between the pressure head and the volumetric moisture content in a soil. The curve is in this study described by the Van Genuchten function (Van Genuchten et al., 1991), with the parameters  $\theta_r$  (the residual water content,  $\text{m}^3 \text{H}_2\text{O m}^{-3}$  soil),  $\theta_s$  (the water content at saturation,  $\text{m}^3 \text{H}_2\text{O m}^{-3}$  soil), and  $\alpha$  ( $\text{m}^{-1}$ ) and  $n$  (dimensionless), the relation between pressure head  $h_m$  (m) and volumetric moisture content  $\theta$  is given by

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + (\alpha|h_m|)^n)^{1-1/n}} \tag{1}$$

The pore size distribution of a soil can be deduced from the water retention curve by the capillary rise equation, assuming that the pores are straight and uniform cylinders

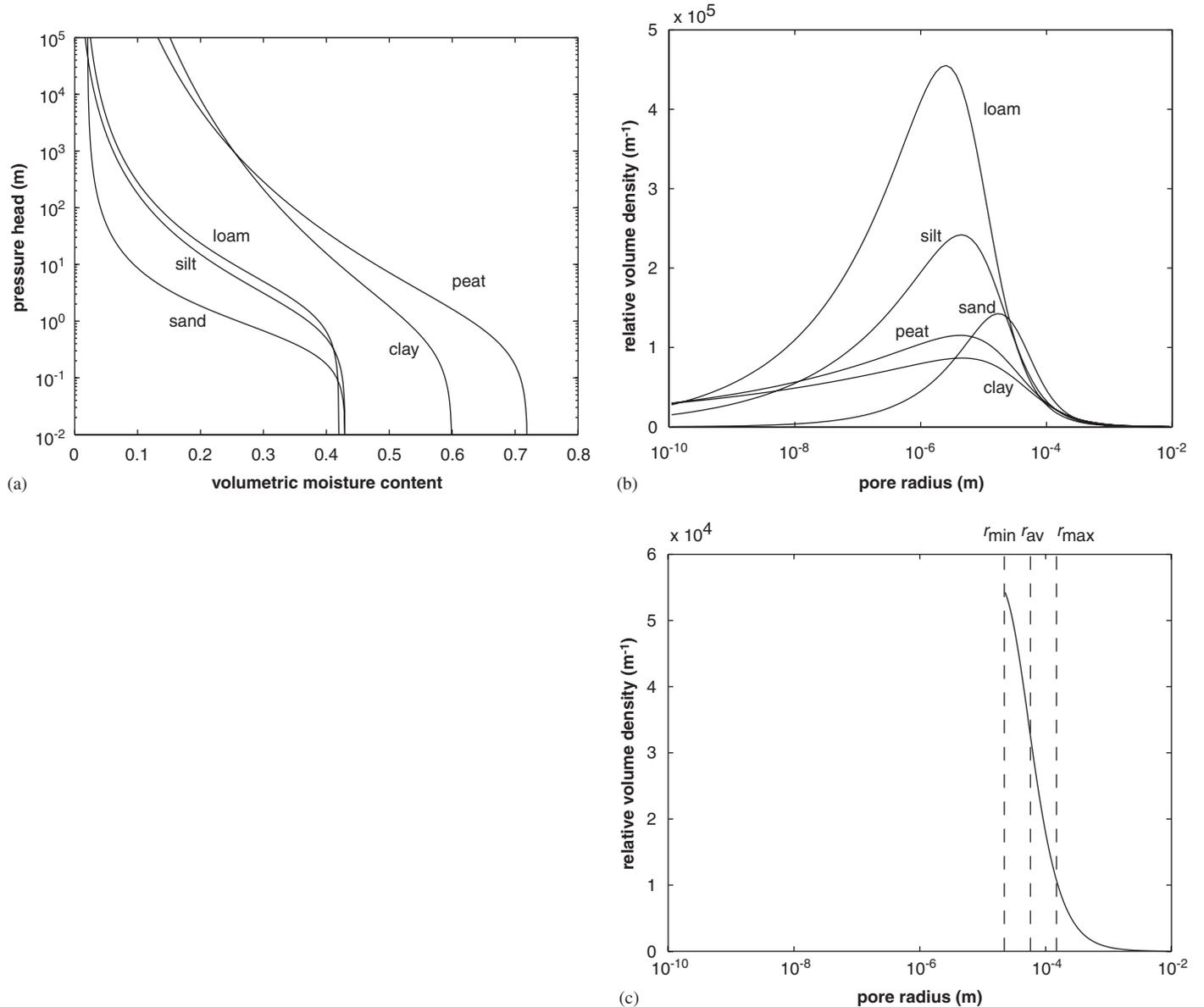


Fig. 1. (a) Water retention curves for a selection of soils from Wösten et al. (1994); sand (B2), silt (B8), clay (B11), loam (B14), peat (B17). (b) Relative pore volume density over pore sizes for the same soils. (c) Relative density of air-filled pore volume for sand (B2, Wösten et al., 1994) at a soil moisture content of 0.30. Indicated are the calculated minimum, maximum and average pore size from the average pore model as used by Arah and Vinten (1995).

(without hysteresis). The radius of the smallest air-filled pore can be calculated from

$$r_{\min} = \frac{2\sigma}{\rho g |h_m|}. \quad (2)$$

In this equation,  $\sigma$  is the surface tension of water ( $\text{N m}^{-1}$ ),  $\rho$  is the density of water ( $\text{kg m}^{-3}$ ) and  $g$  is the gravity constant ( $\text{m s}^{-2}$ ).

In the soil matrix around an air-filled pore, the oxygen status can be calculated as the result of the two major processes: oxygen consumption and diffusion. To do so, assumptions have to be made on these processes. Oxygen consumption can be assumed to be constant throughout the soil matrix in sites where oxygen is present. This zero-order approach is generally used in anaerobiosis models: Arah and Vinten (1995) assume an oxygen consumption of  $50 \mu\text{mol m}^{-3} \text{s}^{-1}$  for respiration, Langeveld and Leffelaar (2002) assume a consumption of  $30 \mu\text{mol m}^{-3} \text{s}^{-1}$ . At steady state, the radial diffusion of oxygen from a circular pore into the matrix equals the oxygen consumption (Arah and Vinten, 1995)

$$D \left( \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right) = Q. \quad (3)$$

In this equation,  $C$  is the oxygen concentration ( $\text{mol m}^{-3}$ ),  $r$  is the radius from the centre of the cylindrical air-filled pore (m),  $D$  is the diffusion coefficient ( $\text{m}^2 \text{s}^{-1}$ ) and  $Q$  is the zero-order oxygen consumption rate ( $\text{mol m}^{-3} \text{s}^{-1}$ ).

The diffusion coefficient refers to the water-saturated matrix between the air-filled pores and has to be corrected for the fact that diffusion in the soil matrix is hampered by soil particles compared to diffusion in free water. Following Arah and Vinten (1995), the diffusion coefficient in water is multiplied with the volumetric fraction of the soil matrix between the air-filled pores that contains water and is further corrected for the tortuosity: the increased path length due to presence of soil particles

$$D = D_w \frac{\theta}{(1 - \varepsilon)} \frac{1}{\tau} \quad (4)$$

with  $D_w$  is the diffusion coefficient in water,  $\varepsilon$  is the air-filled porosity ( $\text{m}^3 \text{air m}^{-3} \text{soil}$ ) and  $\tau$  is the tortuosity (dimensionless).

The oxygen concentration in soil water at the pore boundary,  $C_b$ , can be calculated from the concentration in the air-filled pore, again corrected for the fraction of the soil matrix that contains water (Arah and Vinten, 1995)

$$C_b = \alpha_w C_g \frac{\theta}{(1 - \varepsilon)}, \quad (5)$$

where  $C_g$  is the concentration in the gas-filled pore and  $\alpha_w$  is the solubility of oxygen in water relative to the concentration in air (expressed as  $(\text{m}^3 \text{O}_2 \text{m}^{-3} \text{water}) / (\text{m}^3 \text{O}_2 \text{m}^{-3} \text{air})$ ). The diffusion of oxygen, combined with the consumption of oxygen in the soil matrix, results in a decrease of the oxygen concentration in the soil matrix from  $C = C_b$  at the boundary of the air-filled pore to  $C = 0$

at a certain distance  $R$  from the centre of the pore. This distance  $R$  then defines the aerobic cylinder: all points within the cylinder with radius  $R$  have an oxygen concentration greater than 0.

Integration of Eq. (3) under the condition that  $C = 0$  for radius  $r = R$  results in (Arah and Vinten, 1995)

$$C = \frac{Q}{4D} (r^2 - R^2 \ln(r^2) + R^2 \ln(R^2 - 1)) \quad (6)$$

which describes the oxygen profile within the aerobic cylinder for a point at distance  $r$  from the centre. This

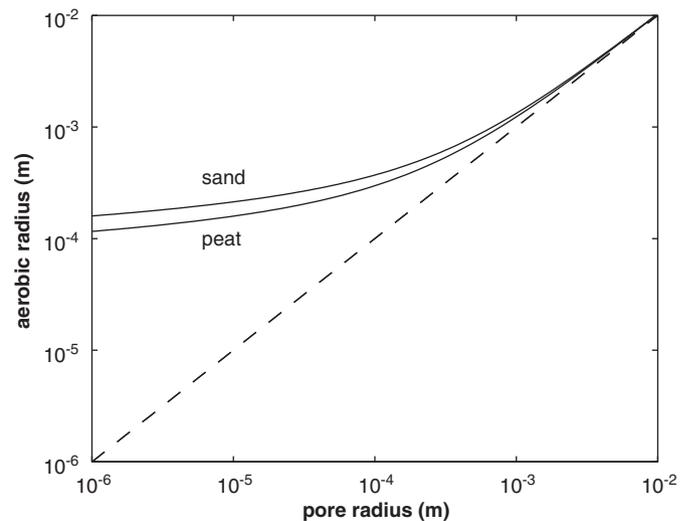


Fig. 2. Radius of the aerobic cylinder as a function of pore radius, calculated with the parameters given in Table 1 for two soil types from Wösten et al. (1994): sand (B2) and peat (B17).

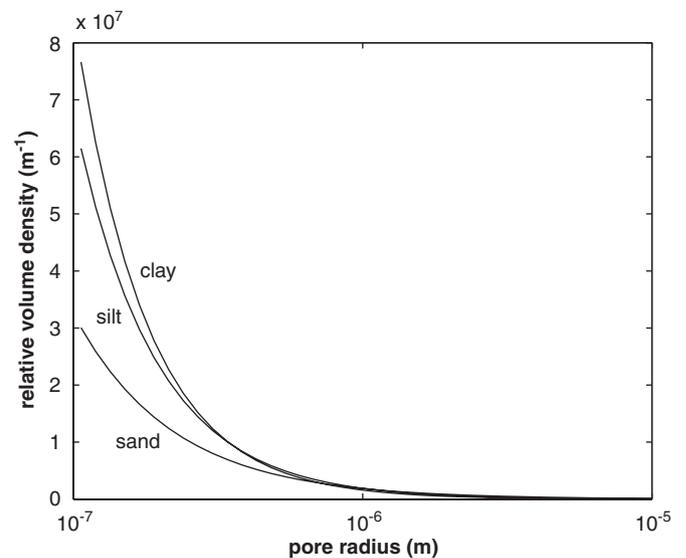


Fig. 3. Relative density of aerobic volume over pore sizes, given for a selection of soils from Wösten et al. (1994): sand (B2), silt (B8), clay (B11). The minimum air-filled pore is set at  $10^{-7}$  m, which corresponds to  $-1.5$  MPa (permanent wilting point).

equation can be solved numerically using  $C = C_b$  at the pore radius  $r = r_{\text{pore}}$ , which results in the radius  $R$  of an aerobic cylinder around a pore with radius  $r_{\text{pore}}$ . In the models described later, this solution is obtained from a combination of bisection, secant and inverse quadratic interpolation (The MathWorks Inc., 2000).

## 2.2. The average pore model

The concept of a pore surrounded by an aerobic cylinder, as described above, is used by Van Veen (1977), Arah and Vinten (1995) and Groenendijk and Kroes (1999). They all perform these calculations for a typical air-filled pore, but the calculation of this typical air-filled pore radius differs for the three descriptions. Van Veen (1977) divides the air-filled pores in 100 classes of equal volume, calculates the minimum pore size for each class from Eq. (2) and takes the average of all classes. Arah and Vinten

(1995) and Groenendijk and Kroes (1999) take the geometrical mean of a minimum and a maximum pore size, assuming a log-normal distribution. Arah and Vinten (1995) calculate the minimum air-filled pore size from the capillary rise Eq. (2), and the maximum as the pore size corresponding to a pressure head of 0.1 m (diameter = 0.03 mm). In Groenendijk and Kroes (1999), the minimum and maximum pore sizes are calculated from Eq. (2), the minimum at the actual pressure head and the maximum at the air entry pressure. When we refer to the ‘average pore’ model, the assumptions by Arah and Vinten (1995) are used.

Finally, the anaerobic fraction  $\phi_{\text{an}}$  of a soil is calculated from the surface area of the oxygenated zone around the average pore ( $\pi R^2$ ), the number of air-filled pores, calculated from the total volume fraction of air-filled pores, assuming that the average pores are parallel and constant in depth, and the spatial distribution of oxygenated zones in a

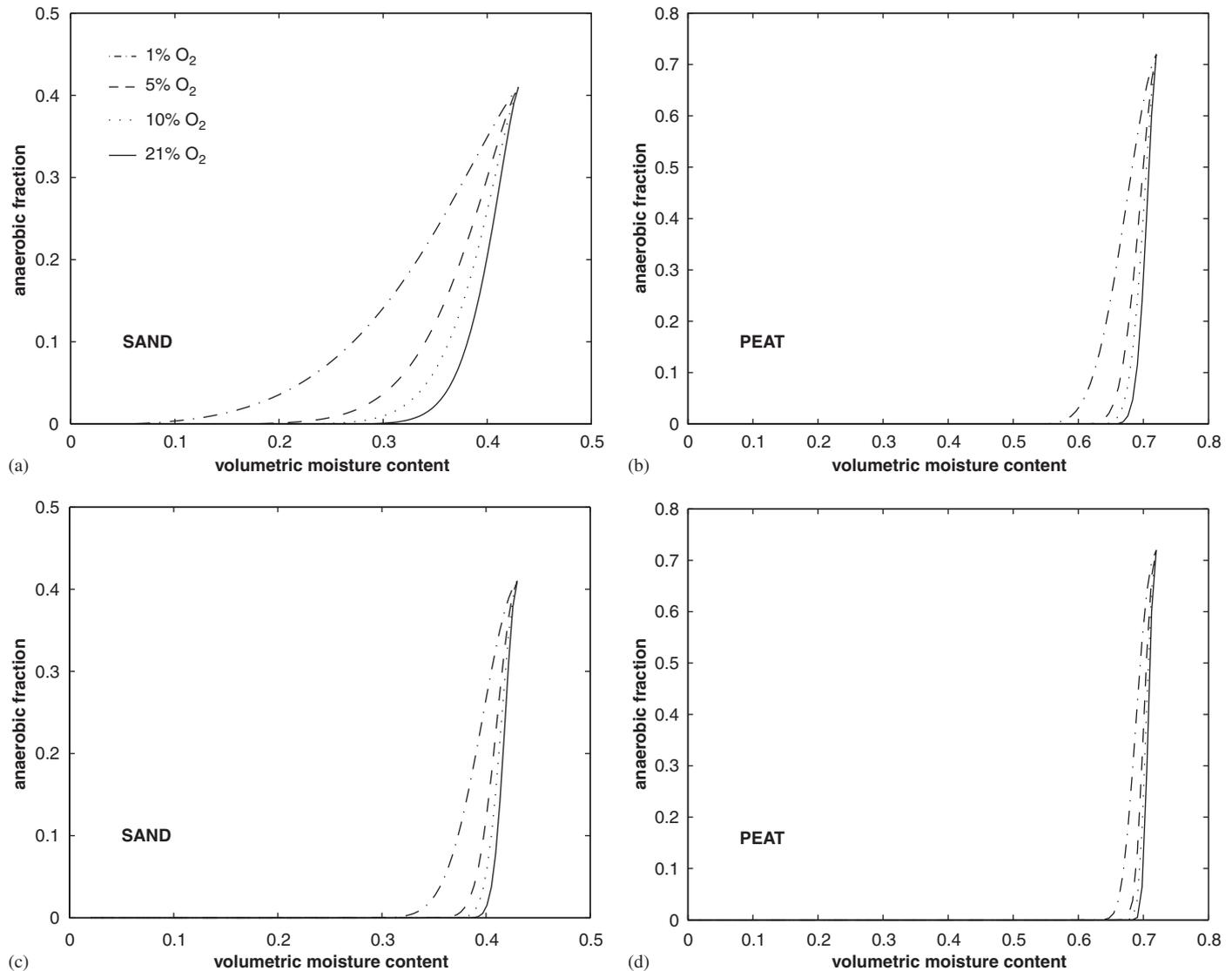


Fig. 4. Predicted anaerobic fraction from (a,b) the average pore model and (c,d) the pore class model as a function of volumetric water content, shown for two soils from Wösten et al. (1994): sand B2, peat B17, at different soil air oxygen concentrations.

cross-sectional unit. Arah and Vinten (1995) suggest that  $n$  oxygenated zones are distributed independently in a cross-section. The probability of an arbitrary point in the cross-section not to be covered by any of these zones, which is equivalent to the anaerobic fraction  $\phi_{\text{an}}$ , equals the  $n$ th power of the probability not to be covered by one of them

$$\phi_{\text{an}} = (1 - \pi R^2)^n \quad (7)$$

This calculation does not account for the possible overlap of air-filled pores and is thus likely to overestimate the anaerobic fraction. Langeveld and Leffelaar (2002) proposed a description of regularly distributed pores, which, in turn, may result in an underestimation of the anaerobic fraction, because the regular distribution minimizes the overlap of aerobic cylinders.

### 2.3. The pore class model

The pore class model proposed here does not use one uniform average air-filled pore size but performs the calculations in Eqs. (3)–(6) for a range of air filled pore sizes which are calculated from the water retention curve according to Eqs. (1) and (2). This is done numerically by dividing the whole range of air-filled pore sizes in 100 classes and calculating the size of the oxygenated cylinder for each class average. The anaerobic fraction is now calculated as the probability that a cross-sectional unit is not covered by  $n$  oxygenated zones of any size, which is equivalent to the product of the contributions for all size classes

$$\phi_{\text{an}} = \prod_{i=1}^{100} ((1 - \pi R_i^2)^{n_i}),$$

where  $i$  is the class number. The number of 100 classes appeared to be sufficiently large: the maximum absolute difference in predicted anaerobic fraction between a simulation with 100 and a simulation with 1000 classes for a sandy soil (B2, Table 2) was  $1.5 \times 10^{-4}$ .

In the following, results from the average pore model (Arah and Vinten, 1995) and the pore class model are compared. This is done with a MATLAB program,<sup>1</sup> in which both concepts were implemented, allowing to inspect intermediate results (e.g. calculated distributions of pore sizes). For the comparison, the parameters in Eqs. (2)–(6) are assumed as in Table 1, and a selection of water retention curves from the Staring series of Dutch topsoils (Wösten et al., 1994) was used. The Van Genuchten parameters for these soils are given in Table 2.

## 3. Results

### 3.1. Average pore assumption

The water retention curves and the distribution of pore sizes for the selected Dutch topsoils differing in texture are

shown in Figs. 1a and b. The assumption of a log-normal distribution for air-filled pores, used in Arah and Vinten (1995) and Groenendijk and Kroes (1999), can be verified to a certain extent by this figure when the soil moisture content is low. At higher soil moisture contents, mainly the right-hand part applies (for better understanding: the peaks of the distributions are in a pore size range of  $10^{-6}$ – $10^{-5}$  m, which are on the boundary of air-filled to water-filled at  $-150$  to  $-15$  kPa). To illustrate this, Fig. 1c shows the volume distribution for a relatively high soil moisture content in a sandy soil, and the ‘average’ air-filled pore radius used by the average pore model.

From Fig. 2 it is clear that the aerobic cylinder is relatively larger for smaller pores. This causes the small pores to contribute relatively more to the aerobic volume. As a consequence, the relative distribution of the aerobic

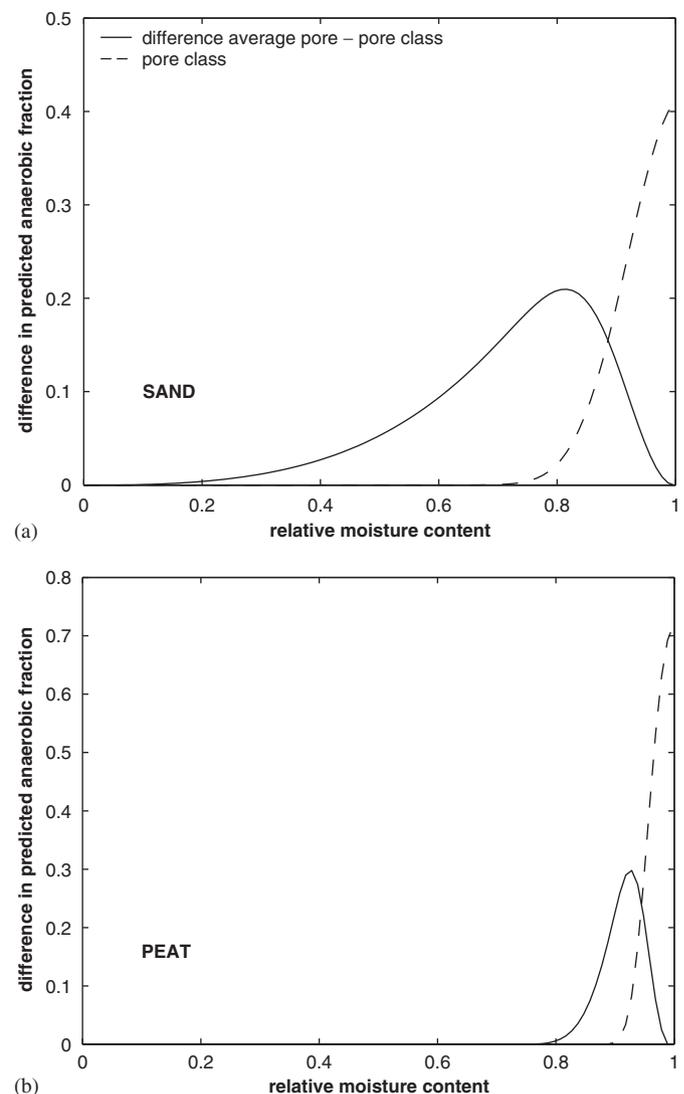


Fig. 5. Difference between predicted anaerobic fraction of the average pore model and the pore class model as a function of relative moisture content, shown for two soils from Wösten et al. (1994): (a) sand B2, (b) peat B17. The dashed line shows the predicted anaerobic fraction from the pore class model.

<sup>1</sup>The program is available from the corresponding author.

volume over pore sizes (Fig. 3) differs from the relative distribution of the pore volume over pore sizes (Fig. 1b).

### 3.2. Average pore model vs. pore classes model

In order to calculate the oxygen profile around a pore, several parameters have to be estimated. The parameters for the comparison are given in Table 1. Anaerobic fractions as a function of soil moisture content predicted from the average pore model and the pore class model are compared in Fig. 4. The pore class model predicts smaller anaerobic fractions, and has a much steeper increase near saturation. The largest difference between the two methods occurs at high moisture contents well before saturation (Fig. 5).

## 4. Discussion

The results show rather large differences between the average pore model and the pore class model: the anaerobic fraction gets up to 30% smaller with the pore class model compared to the average pore model. The difference in model prediction can be compared with the sensitivity of the model to changes in the water retention due to hysteresis. For this purpose, we run both models for sorption and desorption curves of water retention described in a study on hysteresis by Korzilius (1989, unpublished data). The Van Genuchten parameters for these curves are given in Table 2 as well. Results from this comparison are shown in Fig. 6. The analysis showed that the difference between the average pore and the pore class model is larger than the difference between the desorption and sorption curve for two cases (loam and sandy loam),

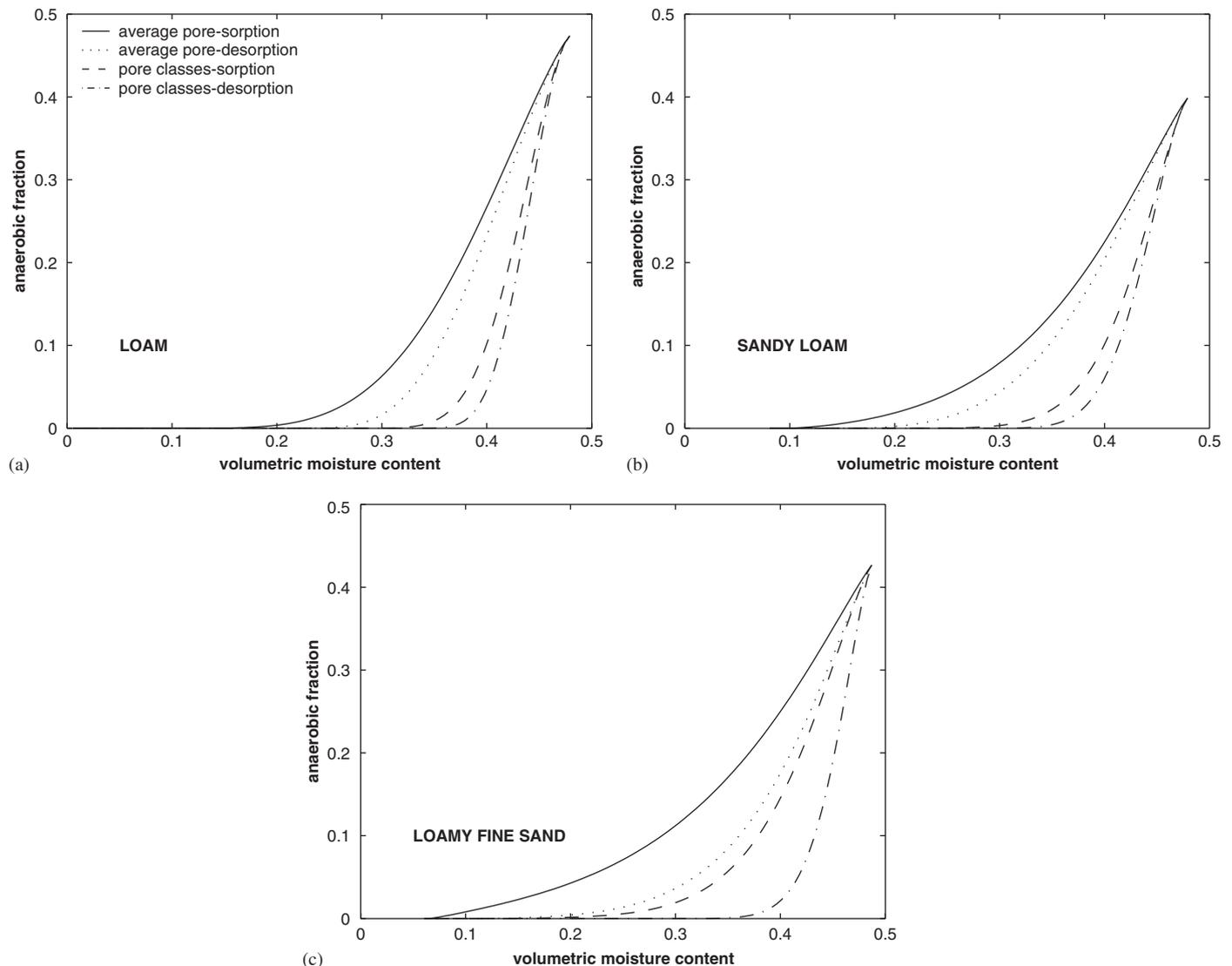


Fig. 6. Hysteresis effect on the outcome of the average pore model and the complete distribution model. Anaerobic fraction as a function of volumetric moisture content, for three soils from Korzilius (1989, unpublished data): (a) loam (Herveld), (b) sandy loam (Lelystad) and (c) loamy fine sand (Sevenum). Results are shown from the average pore model by Arah and Vinten (1995) and from the pore class model.

whereas in one case (loamy fine sand) the differences are roughly equally large.

The models predict a highly non-linear response of anaerobiosis to soil moisture content in all soil types (Fig. 4). Arah and Vinten (1995) compare the outcome of a pore model (average pore) and an aggregate model, and conclude that the aggregate model is much more sensitive to changes in soil moisture. Similarly, our pore class model shows a sharper response to changes in soil moisture within the critical range than the average pore model. This shows that the pore models can yield similar results as the aggregate models, if pore class distribution is included.

Existing soil pore models (Van Veen, 1977; Arah and Vinten, 1995; Groenendijk and Kroes, 1999), which assume an average pore size, overestimate the anaerobic volume because they neglect the disproportionate contribution of the large amount of small pores. A comparison between the existing pore model from Arah and Vinten (1995) and our new model, which uses the complete distribution of pore sizes, shows that the difference between the two models is large and that the average pore model does not give a proper representation of the distribution of air-filled pores. We therefore advise the use of a distribution of pores instead of an average pore size. This strongly increases calculation time, but this could be circumvented by calculating air filled pore distributions for a range of soil moisture levels prior to dynamic simulations.

The highly non-linear response of anaerobiosis to soil moisture predicted by pore models would suggest that soil moisture acts as a switch on anaerobic processes such as denitrification. Such sharp thresholds, however, are dampened by spatial variability both in soil respiration (roots and microbes) and in soil pore size distribution. This spatial variability would thus have to be taken into account when applying the pore model for predictions or analyses of experimental data on anaerobic processes. The use of pore models in dynamic models of carbon and nitrogen requires a separate simulation of the depth profile of the oxygen concentration (Riley and Matson, 2000). The diffusion of oxygen from the air-filled pores into the aerobic cylinders reduces the concentration in the pore itself, and a diffusion of oxygen into the air-filled pores will have to be added. Besides that, diffusion of products from anaerobic reactions out of the soil will have to be simulated, thereby taking into account the possibility of oxidation of these products in case of exposure to O<sub>2</sub> within the soil. These two require the soil to be divided into layers, with diffusion between them driven by concentration gradients.

A dynamic simulation of soil moisture content will enable resolving fluxes of trace gases in time. A suitable

solution will have to be found for periods of decreasing or increasing soil moisture content, when water-filled pores are converted into air-filled pores or vice versa, cases in which the aerobic cylinder is establishing or vanishing. For these situations the steady state assumption is not valid, and they will have to be treated dynamically.

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