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Soil Water Retention: Uni-Modal Models of Pore-Size Distribution Neglect Impacts of Soil Management

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Most models describing soil water retention imply a uni-modal pore-size distribution (PSD). The uni-modal model presented by van Genuchten (termed vanG) is widely used although double-exponential models (termed Dex) implying a bi-modal PSD may better reflect reality. We tested the ability of vanG and Dex models to represent water retention in sandy top- and subsoils with different texture, in soil with contrasting management (Highfield), and in soil exposed to different tillage (Flakkebjerg). Soils were subjected to matric potentials from –10 hPa to –1.5 MPa. For all soils, the bi-modal Dex model showed a better fit to water retention data than the uni-modal vanG model. Neither of the models worked well for highly sorted soils. The vanG model gave a poorer fit for topsoils than for subsoils because of a more pronounced bi-modality of the PSD in topsoils caused by larger soil organic carbon (SOC) content and tillage. For Highfield soils, the root mean squared error (RMSE) of the vanG fit increased from long-term bare fallow (low C content, intensive tillage) to permanent grass (high C content, no tillage) reflecting a more distinct bi-modality of the PSD for well-structured soils. We conclude that uni-modal models should be used with great caution when describing effects of texture and management on PSD and that bi-modal models may provide a better fit to PSD.

Abbreviations: AIC, Akaike's information criterion; d_2, dominating pore size of the structural peak; Dex, double-exponential; PSD, pore-size distribution; RMSE, root mean squared error; SOC, soil organic C; SOM, soil organic matter; V_1, textural void ratio; V_2, structural void ratio; vanG, van Genuchten; VIF, variance inflation factor.

Core Ideas

- A uni- and a bi-modal soil water retention model were evaluated.
- The bi-modal double-exponential model fitted better to soil pore-size distribution.
- The uni-modal model fit was affected by texture, soil organic C, and tillage.
- Uni-modal models are not well suited for describing the pore-size distribution.

The availability of water in soil is crucial for plant growth, microbial activity, and percolation (Rabot et al., 2018). Water storage and availability link intimately to soil PSD and reliable models describing soil water retention become vital when simulating water and solute movement in soil, and availability of water for crop development and soil organic matter (SOM) turnover.

Numerous models for describing soil water retention has been suggested, most of which are uni-modal analytical expressions (Cornelis et al., 2005) such as the one proposed by Brooks and Corey (1964). The uni-modal model suggested by van Genuchten (1980) is probably the most widely used model for describing soil water retention. By May 2018, this publication has received ~10,000 citations of which ~4000 are within the last 5 yr (Clarivate Analytics, 2018). The fitting parameters of the van Genuchten model (here termed vanG) are often used to estimate the unsaturated hydraulic conductivity of soils (Mualem, 1986). Many pedotransfer functions have been developed to predict the vanG parameters from basic soil properties (Cornelis et al., 2001; Minasny et al., 1999; Patil and Singh, 2016). Unsaturated hydraulic conductivity predicted by the vanG parameters are used in simulation models such as Daisy (Hansen et al., 2012) and HYDRUS (Šimunek et al., 2012) when predicting crop production and associated environmental impacts.

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Table 1. Soil textural composition and organic C (SOC) content for the 16 Danish soils at ~0.10-m depth of the Jacobsen (1989) data set listed in order of increasing clay content. The Rosin-Rammler parameters (α and β) were calculated by Eq. [6] and are based on the seven particle-size fractions listed in Jacobsen (1989).

Site	SOC	Clay, <2 μm	Silt, 2–20 μm	Silt, 20–63 μm	Sand, 63–2000 μm	α	β
	g 100 g^{-1} minerals					μm	–
Hals	2.36	2.6	3.4	7.9	86.0	150	1.76
Tylstrup	1.30	3.7	4.9	17.2	74.2	88	3.58
Jyndevad	1.36	4.2	3.9	3.2	88.8	367	1.41
Borris	1.31	5.7	7.8	22.8	63.7	131	0.96
Hornum	1.86	5.8	8.4	13.3	72.5	180	0.93
Travsted	3.38	7.7	6.8	16.2	69.3	189	0.86
Foulum	1.49	7.9	10.1	15.6	66.4	176	0.75
Ødum	1.49	10.1	15.5	20.2	54.3	104	0.71
Årslev	1.36	10.6	14.9	21.1	53.4	95	0.79
Roskilde	1.43	10.8	17.3	19.3	52.7	93	0.74
Askov	1.55	11.0	12.6	16.5	59.9	124	0.77
Rønhave	1.24	14.5	15.6	27.5	42.4	65	0.78
Tystofte	1.18	14.7	16.4	19.5	49.4	75	0.73
Ø. Ulslev	1.38	15.8	15.5	16.5	52.2	102	0.58
Kalø	0.82	17.7	14.4	15.9	52.0	102	0.55
Højer	1.73	18.6	15.4	39.9	26.0	42	1.00

Uni-modal models implicitly assumes a maximum volume of pores at a given tube equivalent pore size. However, presenting the size distribution of pores by frequency for example by numerical differentiation of the water retention curve has documented important deviations from a uni-modal PSD (Eden et al., 2011; Pulido-Moncada et al., 2019; Schjønning, 1992). This calls for a more adequate description of the soil pore system than that obtained by uni-modal expressions. Several non-uni-modal models have been proposed (e.g., Durner, 1994; Poulsen et al., 2006; Ross and Smettem, 1993), including a dual-porosity model for simulating the preferential movement of water and solutes in structured porous media developed by Gerke and van Genuchten (1993). This model involves two overlaying continua reflecting a macropore system and a matrix pore system.

Table 2. Soil textural composition and organic C (SOC) content for the 16 Danish soils at ~0.50-m depth of the Jacobsen (1989) data set listed as in Table 1. The Rosin-Rammler parameters (α and β) were calculated by Eq. [6] and are based on the seven particle-size fractions listed in Jacobsen (1989).

Site	SOC	Clay, <2 μm	Silt, 2–20 μm	Silt, 20–63 μm	Sand, 63–2000 μm	α	β
	g 100 g^{-1} minerals					μm	–
Hals	0.17	2.0	0.5	1.0	96.5	190	3.31
Tylstrup	0.29	3.1	2.4	12.8	81.7	82	5.96
Jyndevad	0.35	3.5	1.9	1.0	93.6	359	2.25
Borris	0.29	11.2	7.3	14.9	66.6	136	0.90
Hornum	0.17	7.2	6.3	13.7	72.8	200	0.88
Travsted	0.35	10.8	6.7	10.8	71.7	194	0.84
Foulum	0.17	13.4	9.6	13.4	63.5	166	0.64
Ødum	0.17	16.5	12.6	16.4	54.4	106	0.60
Årslev	0.17	20.4	12.6	15.9	51.0	78	0.63
Roskilde	0.29	23.8	16.3	11.9	48.0	72	0.49
Askov	0.35	24.5	11.6	14.3	49.6	72	0.55
Rønhave	0.29	19.6	16.5	25.1	38.8	53	0.67
Tystofte	0.29	22.8	15.3	17.9	44.0	58	0.58
Ø. Ulslev	0.23	15.6	13.5	14.1	56.8	120	0.59
Kalø	0.29	26.8	12.4	14.3	46.6	77	0.43
Højer	0.24	7.9	6.4	35.6	50.1	69	3.08

Dexter et al. (2008) presented a double-exponential model (here termed Dex) that provides a bi-modal PSD, that is, a pore-size distribution with two peaks. The two peaks represent the pore space defined by soil texture and that defined by soil structure. By providing parameters with physical meaning, the Dex model may provide a better and more mechanistic description of the PSD of soil in situ (Dexter, 1988; Dexter et al., 2008).

Relying on previously published data, this study evaluates the ability of the uni-modal vanG and bi-modal Dex model to fit water retention data for (i) sandy top- and subsoils with different texture, (ii) soil with contrasting long-term crop rotations, and (iii) a soil subject to different tillage practices.

MATERIALS AND METHODS

The Jacobsen Data Set

Jacobsen (1989) reported hydraulic properties of 16 Danish agricultural soils sampled from topsoil (~0.10 m) and subsoil (~ 0.50 m) layers. Topsoils ranged from loamy sand to silt loam with the main part being sandy loam or loam soils. The Jyndevad and Tylstrup soils were extremely sorted with 51.2 g 100 g^{-1} minerals in the 200- to 500-μm fraction and 51.8 g 100 g^{-1} minerals in the 63- to 125-μm fraction, respectively. Table 1 and 2 show the soil textural composition of top- and subsoils.

All soils were from long-term arable fields derived from the Weichsel glacial stage (glacial deposits: 10 soils; glaciofluvial deposits: Jyndevad), the Saale glacial stage (glacial deposits: Borris and Travsted), the raised Holocene sea floor (Tylstrup and Hals), and one soil sampled on recently reclaimed marine marshland (Højer).

At each site, topsoil was sampled in six plots of about 1 m^2, whereas subsoil was sampled only in one of the plots. For topsoil, three 100-cm^3 soil cores (61-mm diam., 34-mm height) were sampled providing 18 cores per site. For subsoil, nine cores were sampled at each site.

Rothamsted Highfield Ley-Arable Experiment

Data on soil texture, SOC, and pore characteristics for the Highfield long-term ley-arable experiment at Rothamsted Research, UK (51°80′ N, 00°36′ W) was recently published by Jensen et al. (2019) and Obour et al. (2018). Here we use data for four treatments: (i) Bare fallow maintained free of plants by frequent tillage since 1959; (ii) Continuous arable rotation with winter cereals since 1948; (iii) Ley-arable rotation—a 3-yr grass-clover ley followed 3 yr arable since 1948; and (iv) Grassland plowed and reseeded to grass in 1948. The bare fallow treatment was cultivated three to five times per year, arable once a year, ley-arable once in 2 yr (in 6-yr cycle) while grass had not been cultivated since 1947. The arable, ley-arable, and grass treatments were embedded in a randomized block design, whereas the bare fallow plots were not part of the original design and located at one end of the experiment. The soil is silt loam and classifies as Aquic Paludalf (USDA Soil Taxonomy System; Soil Survey Staff, 2014). The parent material includes a silty (loess-containing) deposit overlying and mixed with clay-with-flints (Avery and Catt, 1995).

Soil was sampled in spring 2015. Six 100-cm^3 soil cores (61-mm diam., 34-mm height) were extracted from ~0.10-m depth in each of four replicate plots providing 24 cores per treatment. Further details are given in Jensen et al. (2019) and Obour et al. (2018).

Flakkebjerg Tillage Experiment

We used previously published data on SOC and pore characteristics for the long-term conservation tillage experiment at Flakkebjerg Experimental Station, Denmark (55°19′ N, 11°23′ E). This experiment compares moldboard plowing to 0.20-m depth and direct drilling using a split-plot experiment with four replicates. Soil was sampled in autumn 2013 after 11 yr of different tillage practices. The soil is a sandy loam with 15% clay (<2 μm), 14% silt (2–20 μm), 43% fine sand (20–200 μm), and 27% coarse sand (200–2000 μm) and classifies as Oxyaquic Agriudoll (USDA Soil Taxonomy System; Soil Survey Staff, 2014). The rotation included autumn and spring sown crops (mainly cereals) with all aboveground residues removed.

Six 100-cm^3 soil cores (61-mm diam., 34-mm height) were extracted from the 0.12- to 0.16-m soil layer of each plot providing 24 cores per treatment. Further details can be found in Abdollahi and Munkholm (2017).

Laboratory Measurements

Soil texture was determined on air dry bulk soil (<2 mm) with a combined hydrometer/sieve method (Gee and Or, 2002). Samples from Highfield were treated with hydrogen peroxide to remove soil organic matter (SOM), while this was not done for Flakkebjerg and Jacobsen soils. The content of SOC was measured by dry combustion using a Thermo Flash 2000 NC Soil Analyzer (Thermo Fisher Scientific) for Highfield and Flakkebjerg, and a LECO CNS-1000 analyzer (LECO Corp.) for the Jacobsen soils.

Before measuring soil water retention, the soil cores were placed on the top of a tension table and saturated with water from beneath. For the Jacobsen data set, soil water retention was measured at −4- (Højer only), −10-, −16-, −50-, −100-, −160-, and −500-hPa matric potential using tension tables and pressure plates (Dane and Hopmans, 2002). Samples from the Highfield and Flakkebjerg experiments were drained to −10-, −30-, −100-, −300-, and −1000-hPa matric potential. The soil cores were oven-dried (105°C for 24 h), and bulk density calculated. The Highfield soil contained a significant amount of stones, and bulk density was corrected for weight and volume of >2-mm mineral particles. Soil porosity was estimated from bulk density and particle density. Particle density was measured by the pycnometer method (Flint and Flint, 2002). For Highfield, particle density was measured on one plot from each treatment, and the particle density for the remaining plots were predicted from SOC by a linear regression model. For Flakkebjerg, a particle density of 2.65 g cm^{-3} was used (Abdollahi and Munkholm, 2017).

Water retention at −1.5 MPa was determined on <2-mm air-dry soil for each site and depth for the Jacobsen soils and at plot level for Highfield. For the Jacobsen and Highfield soils a pressure plate system and a WP4-T Dewpoint Potentiometer, respectively, was used (Scanlon et al., 2002). For Flakkebjerg, water retention at −1.5 MPa was predicted based on clay and SOC content using Eq. [1] in Hansen (1976).

Pore-water suction was assumed to relate to an average pore size by the approximate relation:

$$d = -3000/h \qquad [1]$$

where d is the tube-equivalent pore diameter (μm) and h is the soil matric potential (hPa). Equation [1] derives from the physics-based capillary rise equation of Young-Laplace.

Soil Water Retention Models

The water retention data was fitted to the van Genuchten (1980) model (termed vanG):

$$\theta=(\theta_{\mathrm{sat}}-\theta_{\mathrm{res}})\left[1+(\alpha h)^{n}\right]^{-m}+\theta_{\mathrm{res}} \qquad [2]$$

where θ_{sat} and θ_{res} are the water contents at saturation and the residual water content, respectively, h is the soil matric potential, a is a scaling factor for h, and n and m are parameters that control the shape of the curve. The widely used Mualem (1976) restriction ($m = 1-1/n$) was used to prevent over-parametrization (Dexter et al., 2008) and unstable results (van Genuchten et al., 1991). The Mualem restriction is also recommended, when only measured values in the wet range are used (van Genuchten et al., 1991). The PSD predicted by the vanG model was obtained by differentiating Eq. [2] with respect to matric potential:

$$\frac{\mathrm{d}\theta}{\mathrm{d}(\log_{10} h)}=(\theta_{\mathrm{sat}}-\theta_{\mathrm{res}})\left\{\alpha n(\alpha h)^{n-1}(-m)\left[1+(\alpha h)^{n}\right]^{-m-1}\right\}h\ln 10 \qquad [3]$$

The double-exponential model proposed by Dexter et al. (2008) was fitted to water retention data (termed Dex):

$$\theta=C+A_1 e^{(-h/h_1)}+A_2 e^{(-h/h_2)} \qquad [4]$$

where C is the residual water content, A_1 and h_1 describe the textural pore space, and A_2 and h_2 describe the structural pore space. The PSD predicted by the Dex model was obtained by differentiating Eq. [4] with respect to matric potential:

$$\frac{\mathrm{d}\theta}{\mathrm{d}(\log_{10} h)}=-\frac{A_1}{h_1}e^{(-h/h_1)}h\ln 10-\frac{A_2}{h_2}e^{(-h/h_2)}h\ln 10 \qquad [5]$$

The parameters of the vanG model were obtained using the curve-fitting program RETC (van Genuchten et al., 1991), which is based on a nonlinear least-squares optimization approach. Similarly, the parameters of the Dex model were obtained by nonlinear regression analysis to achieve the smallest residual sum of squares.

Calculations and Statistics

The Rosin-Rammler equation (Eq. [2] in Rosin and Rammler, 1933) was fitted to the seven chemically dispersed particle-size fractions listed in Jacobsen (1989), that is, <2, 2 to 20, 20 to 63, 63 to 125, 125 to 200, 200 to 500, and 500 to 2000 µm, for each soil. It can be written as:

$$P(X<x)=1-\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad [6]$$

where $P(X < x)$ is the fraction by weight of particles less than size x, α indicates the coarseness of particles and β indicates the spread of particle sizes. Equation [6] described the particle-size distribution of the soils well, with coefficients of determination (R^2) from 0.95 to 1.00.

For the statistical analysis, the R-project software package Version 3.4.0 (R Foundation for Statistical Computing) was used. Treatment effects for Highfield was analyzed as described in Jensen et al. (2019). The key indices of goodness of fit were Akaike's information criterion (AIC), which was used to compare models with different number of parameters (Akaike, 1973), and the RMSE:

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum(\theta_{\mathrm{meas}}-\theta_{\mathrm{fitted}})^2} \qquad [7]$$

where N is the number of matric potentials. A smaller or more negative AIC indicates better model performance.

Multiple linear regression was used to identify how structural void ratio (V_2) related to SOC, soil texture, and void ratio. Structural void ratio was calculated as follows:

$$V_2 = A_2/(1\text{-}P) \qquad [8]$$

where A_2 is the Dex model estimate of structural pore space, and P is porosity. Likewise, textural void ratio (V_1) was calculated by relating A_1 to (1-P).

The variance inflation factor (VIF) was calculated when more than one predictor was used in the regression. The VIF expresses the degree of multicollinearity among the predictors. Upper value limits of VIF for non-erroneous conclusions from multiple regressions has been set to five (Rogerson, 2001) or ten (Kutner et al., 2004).

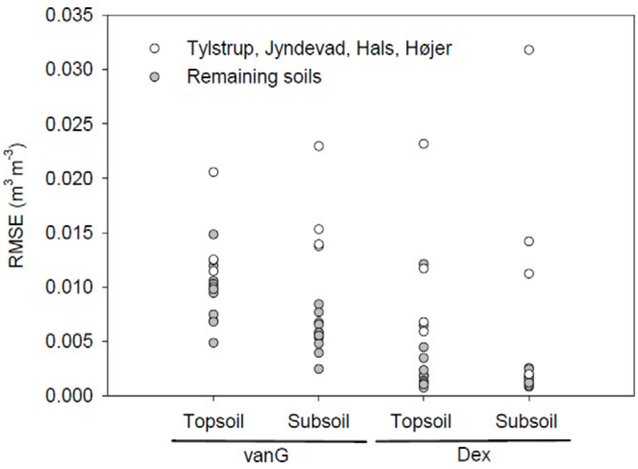

Fig. 1. The root mean squared error (RMSE) value for the Danish top- and subsoil of the Jacobsen data set using the van Genuchten (vanG) or double-exponential (Dex) model.

RESULTS

Jacobsen Data Set

The soils differed in their textural composition and SOC content (Tables 1 and 2). In the topsoil, clay ranged from 2.6 to 18.6 g 100 g^{-1} minerals and SOC from 0.82 to 3.38 g 100 g^{-1} minerals, whereas the range in the subsoil was from 2.0 to 26.8 g clay 100 g^{-1} minerals and from 0.17 to 0.35 g SOC 100 g^{-1} minerals. The α-parameter for topsoil ranged from 42 to 367 µm and for subsoil from 53 to 359 µm. The Jyndevad soil, however, stand out being very coarse textured ($\alpha_{\mathrm{topsoil}}$ = 367 µm, $\alpha_{\mathrm{subsoil}}$ = 359 µm), and the range changed to 42 to 200 µm if omitting Jyndevad. The β-parameter describes the spread of particle sizes, with large values indicating that the soil is well sorted (a narrow range of particle sizes), and small values indicating that the soil is graded with an evenly distributed mass of particles across size classes. The β-parameter for topsoil ranged from 0.55 to 3.58 and for subsoil from 0.43 to 5.96. The 12 glacial till soils, however, had a narrow range from 0.43 to 0.96, whereas Hals, Tylstrup, Jyndevad, and Højer were highly sorted with $\beta > 1$ (Tables 1 and 2).

For topsoil, mean values of AIC were −58.6 and −70.6 and mean RMSE were 0.011 and 0.005 $m^3\ m^{-3}$ using vanG and Dex, respectively. For subsoil, mean values of AIC were −63.2 and −75.1 and mean RMSE were 0.008 and 0.005 $m^3\ m^{-3}$. However, the four highly sorted soils ($\beta > 1$) had relatively poor goodness of fit measures both when using the vanG and Dex models (Fig. 1, Tables S1 and S2).

When omitting the highly sorted soils in the calculation of mean AIC and RMSE values, the vanG model gave AIC values of −59.6 and −66.8 and RMSE values of 0.009 and 0.006 $m^3\ m^{-3}$ in top- and subsoil, respectively. The Dex model gave AIC values of −75.1 and −80.9 and RMSE values of 0.003 and 0.002 $m^3\ m^{-3}$ in top- and subsoil, respectively. The lower AIC and RMSE values obtained for the Dex compared with the vanG model indicate that the Dex model provides a better description of data.

We tested the correlation between the structural void ratio (V_2) and the variables α, β, void ratio, SOC, and clay content. This was done for both top- and subsoils and with and without exclusion of the highly sorted soils ($\beta > 1$). For topsoil samples V_2 could be well predicted by log(β) and clay content:

$$V_2 = 0.558^{***}(\pm 0.118) \times \log(\beta) - 0.011^{*}(\pm 0.005) \times \mathrm{clay} + 0.424^{***}(\pm 0.048),$$
$$s = 0.068,\ R^2 = 0.84 \qquad [9]$$

Excluding the highly sorted samples from topsoil gave:

$$V_2 = 0.878^{***}(\pm 0.143) \times \beta - 0.441^{**}(\pm 0.110), s = 0.057,$$
$$R^2 = 0.79 \qquad [10]$$

For subsoil samples V_2 could be well predicted by log(β) and α:

$$V_2 = 0.592^{***}(\pm 0.078) \times \log(\beta) - 0.001^{**}$$
$$(\pm 0.0003) \times \alpha + 0.184^{**}(\pm 0.050),$$
$$s = 0.100, R^2 = 0.85 \qquad [11]$$

Excluding the highly sorted samples from subsoil gave:

$$V_2 = 0.289^{***}(\pm 0.025) \times \beta, s = 0.057, R^2 = 0.55 \qquad [12]$$

In Eq. [9]–[12], the numbers in parentheses are standard errors of estimate, and s is the standard deviation of the predicted value. When developing the four models, we tested for multicollinearity and interaction among the predictors, but found only low VIF values and no significant interactions.

Rothamsted Highfield Ley-Arable Experiment

The soils at Highfield ranged from 0.84 to 4.04 g SOC 100 g^{-1} minerals and soil texture was in general not significantly different between treatments (Table 3). Thus, the effect of contrasting long-term management could be investigated without confounding effects related to variations in soil type. The Dex model generally fitted the water retention data for the contrasting treatments well (Fig. 2a).

Mean values of AIC, when using the vanG and Dex models were −43.8 and −69.1, respectively. Similarly, mean values of RMSE were larger when using the vanG compared with the Dex model with values of 0.016 and 0.002 m^3 m^{-3}, respectively. The RMSE when using the vanG model increased from 0.010 to 0.028 m^3 m^{-3} with an increase in SOC from 0.84 to 4.04 g 100 g^{-1} minerals (Fig. 3), whereas no systematic error was observed when using the Dex model (P = 0.532). Parameter estimates and goodness of fit measures for the 16 individual plots can be seen in Table S3.

Table 3. Soil textural composition and organic carbon (SOC) content of the four treatments from Highfield. Within rows, letters denote statistical significance at *P* < 0.05 for the comparison of Arable, Ley-arable, and Grass. Data from Jensen et al. (2019).

Treatment	SOC	Clay, <2 μm	Silt, 2–20 μm	Silt, 20–63 μm	Sand, 63–2000 μm
		g 100 g^{-1} minerals			
Bare fallow	0.90	27.0	24.9	33.5	14.6
Arable	1.73a†	26.4	26.3	31.8	15.5
Ley-arable	2.16a†	25.5	26.1	32.4	16.0
Grass	3.29b†	26.1	27.2†	31.9	14.8

† Indicates if bare fallow is significantly different from the other treatments based on a pairwise ***t*** test.

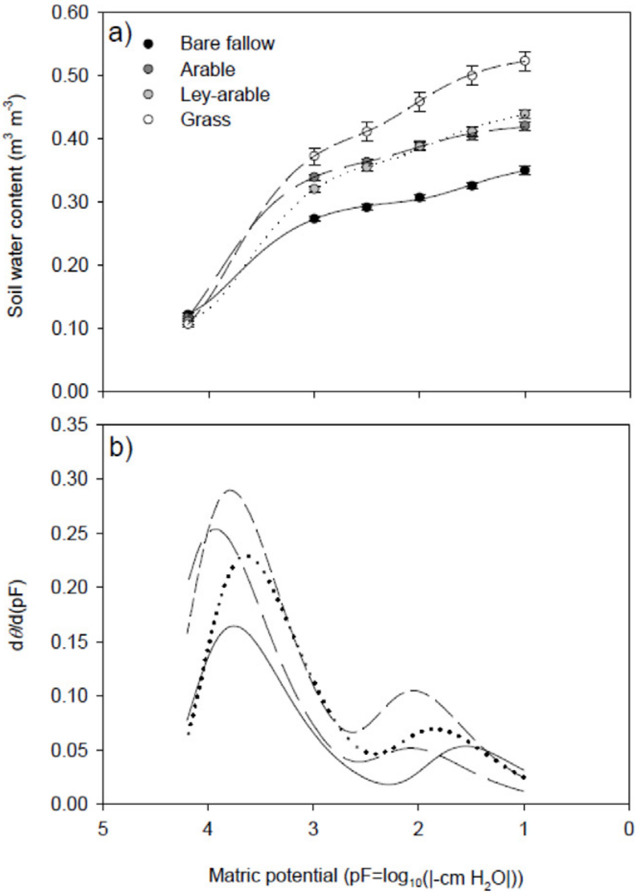

Fig. 2. (a) Measured volumetric water content for the four treatments at Highfield and fits of the double-exponential (Dex) model as a function of matric potential. The standard error of the mean is indicated (*n* = 4). (b) Pore-size distribution [dq/d(pF)] as a function of matric potential for the four treatments. Equation [5] was used to obtain the pore-size distributions.

Textural (V_1) and structural void ratio (V_2) increased with increasing SOC content and decreasing tillage intensity (V_1: $R^2 = 0.91, P < 0.001$, V_2: $R^2 = 0.74, P < 0.001$). The dominating pore size of the structural peak (d_2) was 86 μm for the bare fallow

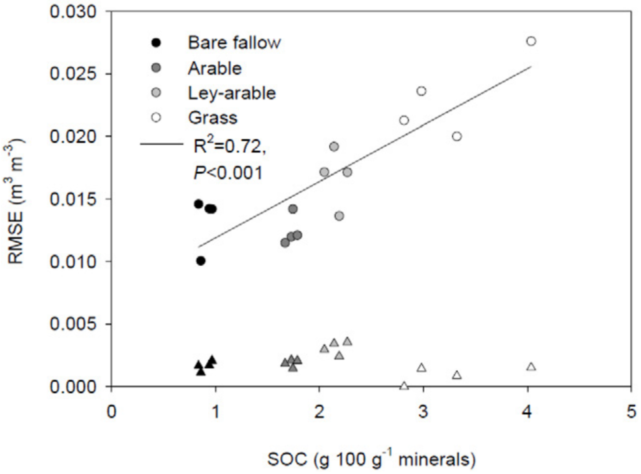

Fig. 3. The root mean squared error (RMSE) value as a function of soil organic carbon (SOC) for the four treatments at Highfield using the van Genuchten (vanG) model (circle symbols) and the double-exponential (Dex) model (triangle symbols).

Table 4. Estimated parameters of the double-exponential model (Dex) of the four treatments from Highfield. Within rows, letters denote statistical significance at $P < 0.05$ for the comparison of Arable, Ley-arable and Grass. d_1 and d_2 indicate the dominating pore size of the textural and structural peak, respectively, and were estimated by Eq. [1].

	Parameters of the Dex model						
Treatment	C	A_1	h_1	d_1	A_2	h_2	d_2
	$m^3\ m^{-3}$	$m^3\ m^{-3}$	hPa	μm	$m^3\ m^{-3}$	hPa	μm
Bare fallow	0.110	0.195	5729	0.5	0.061	35	86
Arable	0.068a†	0.305ab†	8707b†	0.3	0.051a	97b†	31
Ley-arable	0.104b	0.271a†	4379a	0.7	0.073a	63a	48
Grass	0.080ab†	0.345b†	6216a	0.5	0.110b†	102b†	29

† Indicates if bare fallow is significantly different from the other treatments based on a pairwise *t* test.

treatment, while it was significantly lower for the arable and grass treatments, and in between for ley-arable treatment (Table 4).

Flakkebjerg Tillage Experiment

Moldboard plowing to 0.20-m depth and direct drilling had contents of 1.25 and 1.15 g SOC 100 g^{-1} minerals, respectively, in the 0.12- to 0.16-m layer. The Dex model fitted the two treatments well (Fig. 4), and better compared with the vanG model as revealed by lower mean AIC and RMSE values (Plowing: $AIC_{vanG} = -56.7$ and $AIC_{Dex} = -59.5$, $RMSE_{vanG} = 0.007\ m^3\ m^{-3}$ and $RMSE_{Dex} = 0.003\ m^3\ m^{-3}$; Direct drilling: $AIC_{vanG} = -58.0$ and $AIC_{Dex} = -69.5$, $RMSE_{vanG} = 0.005\ m^3\ m^{-3}$ and $RMSE_{Dex} = 0.001\ m^3\ m^{-3}$).

Structural void ratio (V_2) for moldboard plowing and direct drilling was 0.30 and 0.19, respectively. The dominating pore size of the structural peak (d_2) was 52 μm for direct drilling and 96 μm for moldboard plowing. Parameter estimates and goodness of fit measures for the eight individual plots can be seen in Table S4.

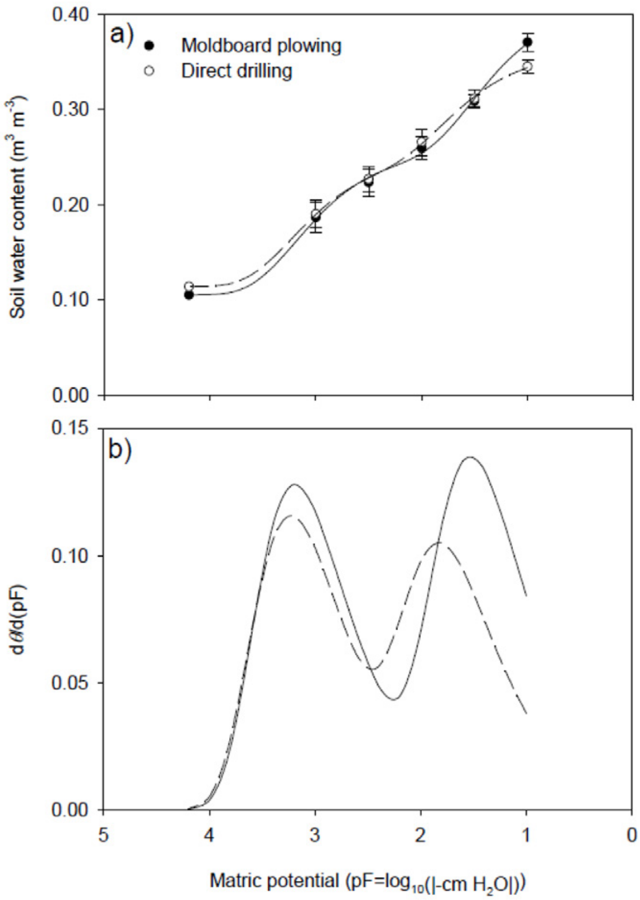

Fig. 4. (a) Measured volumetric water content for moldboard plowing to 0.20-m depth and direct drilling and fits of the double-exponential (Dex) model as a function of matric potential. The standard error of the mean is indicated ($n = 4$), except for pF 4.2 which is predicted based on Eq. [1] in Hansen (1976). (b) Pore-size distribution [dq/d(pF)] as a function of matric potential for the two treatments. Equation [5] was used to obtain the pore-size distributions.

DISCUSSION

Model Fit

The Dex model provided a better fit to soil water retention data than the vanG model for the Jacobsen glacial till top- and subsoils. This was also true for contrasting treatments from Highfield and Flakkebjerg. Thus, the PSD for these soils was better described with a bi- rather than a uni-modal model. This is in accordance with Schjønning (1992) who found the vanG model unable to describe the double-peak pattern for PSD in glacial till soils. Further, Dexter et al. (2008), Berisso et al. (2012), and Zhou et al. (2017) found that the Dex model fitted their data better than the vanG model. Dexter et al. (2008) based their analysis on 42 Polish soils (26 topsoils, 6 samples from 0.30- to 0.35-m depth, and 10 subsoils) ranging from 2 to 25 g clay 100 g^{-1}, Berisso et al. (2012) focused on a sandy clay loam ranging from 19 to 27 g clay 100 g^{-1}, and Zhou et al. (2017) investigated clay loam paddy soil (~20 g clay 100 g^{-1}). Our study included soils ranging in clay content from 2.0 to 30.0 g 100 g^{-1} minerals, substantiating that the Dex model is superior for soils < 30 g clay 100 g^{-1} minerals. Thus, uni-modal models seem too simplistic for describing the size distribution of pores in most soils with less than 30 g clay 100 g^{-1} minerals. A range of papers comparing other bi-modal models with uni-modal models reached similar conclusions (e.g., Durner, 1994). However, the Dex model is less parameter demanding than other proposed bi-modal models, making it easier to apply to datasets with a restricted number of measurement points.

Neither of the models worked well for highly sorted soils ($\beta > 1$). This finding calls for alternative water retention models for soils with a narrow distribution of pore sizes. Dexter et al. (2008) mentioned the problems associated with the use of the Dex model for uniform sands. However, we emphasize that the Dex as well as the vanG model cannot describe highly sorted soils well regardless of the dominating particle size.

Pitfalls using Uni-Modal Models—Effects of Soil Organic Carbon and Tillage

For the Jacobsen data set, the vanG model provided a better description of subsoils than of topsoils (Fig. 1). This was ascribed to a more distinct bi-modal PSD for topsoil. The bi-modality reflects that topsoils were larger in SOC content and exposed to tillage (Fig. 5).

Tillage increases the amount of large structural pores. The effect of structure forming agents in subsoil are much reduced and limits the structural pore space at depth. Similarly, the systematic increase in RMSE with increasing SOC content for Highfield (Fig. 3) could be ascribed to a more pronounced bi-modal behavior (Fig. 2b), most clearly seen for soils from the grass treatment (Fig. 6a and 6b).

However, the vanG model overestimated the pore volume in the size range 10- to 30-µm (pF 2.5–2) and underestimated the pore volume at pF 3 and 1 markedly for both treatments, although more pronounced for the grass treatment (Fig. 6c and 6d).

Due to its absorptive capacity for water, the presence of SOC may increase the textural pore space especially in soils with <20 g clay 100 g^{-1} (Rawls et al., 2003). The structural pore space is mainly affected by SOC through improved aggregation (Bronick and Lal, 2005). At Highfield, SOC affected both V_1 and V_2 positively whereas the estimate of the mean size of structural voids (d_2) decreased with increasing SOC content. For Flakkebjerg, where plowing was compared with direct drilling, both V_2 and d_2 increased with tillage intensity. The limited effect of tillage on V_2 when comparing grass and bare fallow at Highfield suggests that the effect of SOC on soil structure outweighed any effect of tillage. Interestingly, d_2 was larger for bare fallow than for grass suggesting that tillage introduces large pores as also observed for soils from Flakkebjerg. Zhou et al. (2017) found that SOC promoting management increased the structural porosity when comparing organic manure with unfertilized and inorganically fertilized treatments being in correspondence with our results from Highfield.

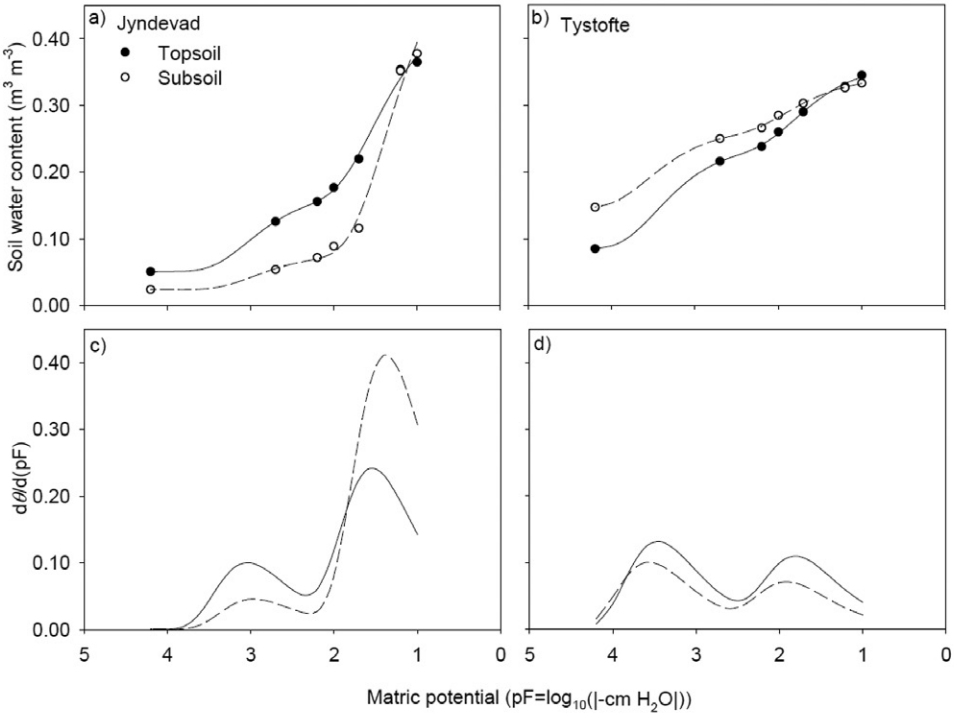

Fig. 5. (a, b) Measured volumetric water content for Jyndevad and Tystofte top- and subsoils of the Jacobsen data set and fits of the double-exponential (Dex) model as a function of matric potential. (c, d) Pore-size distribution [dq/d(pF)] as a function of matric potential for Jyndevad and Tystofte top- and subsoils. Equation [5] was used to obtain the pore-size distributions.

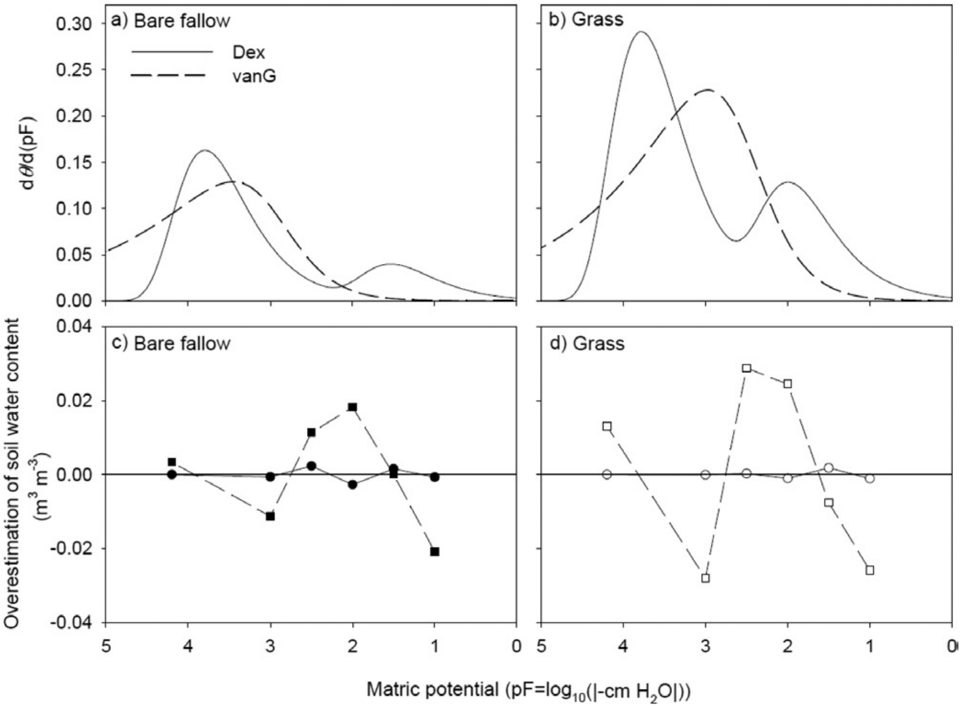

Fig. 6. Pore-size distribution [dq/d(pF)] as a function of matric potential for (a) the bare fallow and (b) the grass treatment at Highfield either obtained by differentiating the double-exponential (Dex) model (solid line) or the van Genuchten (vanG) model (dashed line). Equation [3] and [5] were used to obtain the pore-size distributions predicted by the vanG and the Dex models, respectively. Overestimation of soil water content (fitted-measured values) as a function of matric potential for (c) the bare fallow and (d) the grass treatment when fitted to the vanG model (square symbols) and the Dex model (circle symbols).

Structural Void Ratio

The structural void ratio (V_2) is an important parameter for soil functions such as air exchange and water availability for plants. We used V_2 rather than volumetric water content to allow for comparisons across soils with different bulk density. As discussed above SOC contents and tillage intensity are important drivers for V_2, but soil texture also affects V_2 through a positive relation to β (Eq. [9] to [12]) indicating that the more sorted soils have larger V_2 than graded soils. This agrees with Ehlers and Claupein (1994), who reported that graded coarse-textured soils readily compact to high densities. Similarly, Schjønning and Thomsen (2013) found that graded soils low in SOC showed a hard-setting behavior. A low V_2 may affect root growth negatively and reduce soil gas exchange. Therefore, SOC promoting management should target graded soil low in SOC.

CONCLUSIONS

Predicting soil water retention by the uni-modal vanG model is likely to introduce larger error in top—than in subsoils and errors is likely to be larger for well-structured soils than for structurally degraded soils. Ignoring management-derived effects (e.g., derived from changes in SOC and tillage) on PSD may compromise modeling of key soil processes and simulations based on pedotransfer functions. We found that the more flexible bi-modal Dex model provides an adequate description of the PSD and we discourage uncritical use of uni-modal models.

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SUPPLEMENTAL MATERIAL

Supplemental material is available with the online version of this article. The supplemental document presents parameter estimates of the van Genuchten and double-exponential model for the 16 Danish top- and subsoils of the Jacobsen data set, the 16 plots at Highfield, and the 8 plots at Flakkebjerg.

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