Agriculture and Agri-Food Canada | Agriculture et Agroalimentaire Canada

Use of Bimodal Hydraulic Property Relationships to Characterize Soil Physical Quality

Dan Reynolds, Craig Drury, Xueming Yang, and Lori Phillips

Agriculture & Agri-Food Canada, Harrow Research & Development Centre, Harrow, Ontario, Canada

Introduction

Soil hydraulic properties have a predominating impact on soil physical quality (**SPQ**) because they directly or indirectly control:

- storage of soil water and soil air
- infiltration and drainage
- nutrient leaching
- soil microbial dynamics and activity
- greenhouse gas (GHG) generation
- sequestration of soil organic carbon

Soil hydraulic properties are often better described using "bimodal" water release, ***θ*(*h*)**, and hydraulic conductivity, ***K*(*h*)**, functions which combine:

- large-pore "structure domain" $\theta_S(h)$ and $K_S(h)$
- small-pore "matrix domain" $\theta_M(h)$ and $K_M(h)$

Few studies have assessed the physical quality of soils with distinct structure and matrix domains

Objectives:

1) Show how closed-form van Genuchten (1980) $\theta(h)$ and $K(h)$ functions might be fitted to bimodal $\theta(h)$ and $K(h)$ data.
2) Use fitted bimodal $\theta(h)$ and $K(h)$ functions to characterize the SPQ of soils with distinct structure and matrix domains.

Relationships

1. Bulk Soil Water Release Curve, $\theta_B(h)$: (adapted from McCoy & Stehouwer, 1998)

$$\theta_B(h) = \sum_{i=1}^{2}\left(\frac{P_i}{A_i^{m_i}}\right) + P_R \qquad (1)$$

i = 1 → structure domain ; i = 2 → matrix domain

P_1 = structure domain porosity ; P_2 = matrix domain porosity
P_R = residual (non-participating) porosity

P_B = bulk soil porosity = $P_1 + P_2 + P_R$

$$A_i = \left[1 + (\alpha_i h)^{n_i}\right] \quad ; \quad h = \text{tension head}$$

α_i , n_i , m_i = van Genuchten (1980) curve fitting parameters

2. Bulk Soil Hydraulic Conductivity Function, $K_B(h)$: (adapted from Priesack & Durner, 2006)

$$K_B(h) = K_{BS}\left(\sum_{i=1}^{2}\frac{\omega_i}{A_i^{m_i}}\right)^P \left(\sum_{i=1}^{2} B_i\left[1-\frac{C_i}{A_i^{m_i}}\right] \Big/ \sum_{i=1}^{2} B_i\right)^V \qquad (2)$$

ω_i = structure – matrix proportions

$$B_i = \omega_i\alpha_i \quad ; \quad C_i = (\alpha_i h)^{n_i - q}$$

K_{BS} = bulk soil saturated hydraulic conductivity, *Ksat* (**measured**)

K_{MS} = matrix domain *Ksat* $= K_{BS}\left(\frac{\omega_M\alpha_M}{\omega_M\alpha_M + \omega_S\alpha_S}\right)^V \omega_M^P$

K_{SS} = structure domain *Ksat* = $K_{BS} - K_{MS}$

Mualem (1976) "series-parallel" pore distribution model:
P = 0.5 ; q = 1 ; V = 2

Burdine (1953) "parallel" pore distribution model:
P = 2 ; q = 2 ; V = 1

3. Bulk Soil Pore Size Distribution (*PSD*) Function, $P_B(h)$:

$$P_B(h) = \ln(10)\sum_{i=1}^{2}\left(\frac{m_i n_i P_i(\alpha_i h)^{n_i}}{A_i^{(m_i+1)}}\right) \quad \text{versus} \quad d_e \qquad (3)$$

d_e = G/h = equivalent pore diameter
G = proportionality constant

$$d_i = G\alpha_i m_i^{(1/n_i)} \text{ = PSD peaks for structure \& matrix domains} \qquad (4)$$

4. Field Capacity Water Content for Structure Domain (θ_{SFC}) and Matrix Domain (θ_{MFC}) (adapted from Assouline & Or, 2014):

$$\theta_{SFC} = P_1 - \frac{K_{SFC}(t_{FC})}{0.092(z)} \quad ; \quad \theta_{MFC} = P_2 - \frac{K_{MFC}(t_{FC})}{0.092(z)}$$

t_{FC} = 3 days = specified time for gravity drainage from saturation

K_{SFC} , K_{MFC} = field capacity hydraulic conductivity for structure & matrix domains

z = 30 cm = specified primary crop rooting depth

5. Plant-Available Air (*AC*) and Water (*PAWC*) Capacities for Structure Domain and Matrix Domain:

AC_S = structure domain = $P_1 - \theta_{SFC}$; AC_M = matrix domain = $P_2 - \theta_{MFC}$

$PAWC_S$ = structure domain = $\theta_{SFC} - PWP_S$; $PAWC_M$ = matrix domain = $\theta_{MFC} - PWP_M$

Example Results

Fig. 1. Desorption curve data from packed soil aggregates plus fitted Eq. (1) delineating bulk soil, $\theta_B(h)$, matrix domain, $\theta_M(h)$, structure domain, $\theta_S(h)$, and residual domain, θ_R. P_M and P_S are matrix domain and structure domain porosities, respectively.

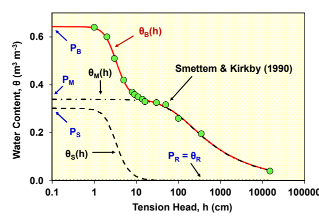


Fig. 2. Predicted pore size distributions (*PSD*) are based on Fig. 1 and Eq. (3). The d_e values at the matrix and structure domain peaks (modes) are determined using Eq. (4).

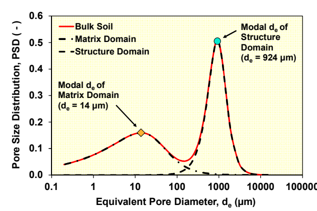


Fig. 3. Hydraulic conductivity data from packed soil aggregates plus Eq. (2) predictions for bulk soil, $K_B(h)$, matrix domain, $K_M(h)$, and structure domain, $K_S(h)$.

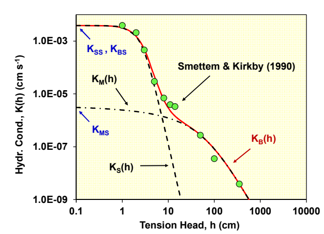


Fig. 4 (packed aggregates). Structure and matrix domain porosities contribute about equally to bulk soil porosity.

Bulk soil field capacity water content determined largely by matrix domain.

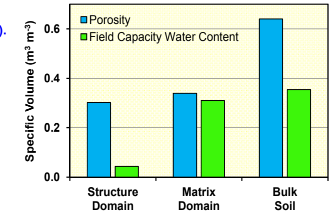


Fig. 5 (packed aggregates). Bulk soil has excellent air and water capacities: AC = 0.29 m³ m⁻³ ; PAWC = 0.31 m³ m⁻³.

However:
Structure domain is severely water-limited, i.e. PAWC < 0.10 m³ m⁻³. Matrix domain is severely aeration-limited, i.e. AC < 0.10 m³ m⁻³.

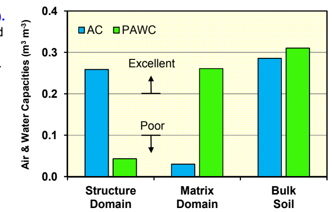
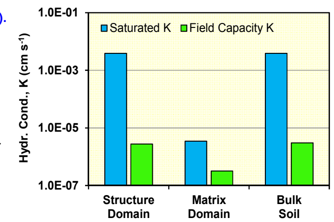


Fig. 6 (packed aggregates). Bulk soil Ksat and K_{FC} are controlled by structure domain Ksat and K_{FC}, respectively.

Using the Meyer & Gee (1999) criteria, drainage at field capacity is "minor" in matrix domain (K_{FC} = 3 x 10^{-7} cm s^{-1}), but significant in structure domain (K_{FC} = 3 x 10^{-6} cm s^{-1}).



Implications

- Although the SPQ of bulk soil may be good, the SPQ of the structure and/or matrix domains may be limited.
- The structure domain can be droughty and potentially prone to drainage-induced leaching of nutrients.
- The matrix domain can be poorly aerated and potentially prone to GHG generation.
- Maximizing the economic and environmental performance of field-crop production may require targeted improvement of structure or matrix SPQ.

References

Assouline, S., Or, D., 2014. The concept of field capacity revisited: defining intrinsic static and dynamic criteria for soil internal drainage dynamics. Water Resources Res. 50, 4787-4802.
Burdine, N.T., 1953. Relative permeability calculations from pore size distribution data. Petroleum. Trans. Am. Inst. Mining, Metall. Eng. 198, 71-77.
McCoy, E.L., Stehouwer, R.C., 1998. Water and nutrient retention properties of internally porous inorganic amendments in high sand content root zones. Jour. of Turfgrass Management 2 (4), 49-69.
Meyer, P.D., Gee, G.W., 1999. Flux-based estimation of field capacity. Jour. of Geotechnical & Geoenvironmental Eng. 125 (7), 595-599.
Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Res. 12, 513-522.
Priesack, E., Durner, W., 2006. Closed-form expression for the multi-modal unsaturated conductivity function. Vadose Zone Jour. 5, 121-1124.
Smettem, K.R.J., Kirkby, C., 1990. Measuring the hydraulic properties of a stable aggregated soil. Jour. of Hydrology 117, 1-13.

Acknowledgements

Funding for this study was provided by the Science & Technology Branch of Agriculture & Agri-Food Canada.

dan.reynolds@agr.gc.ca

Canada