Diffusivity-Based Characterization of Plant Growth Media for Earth and Space

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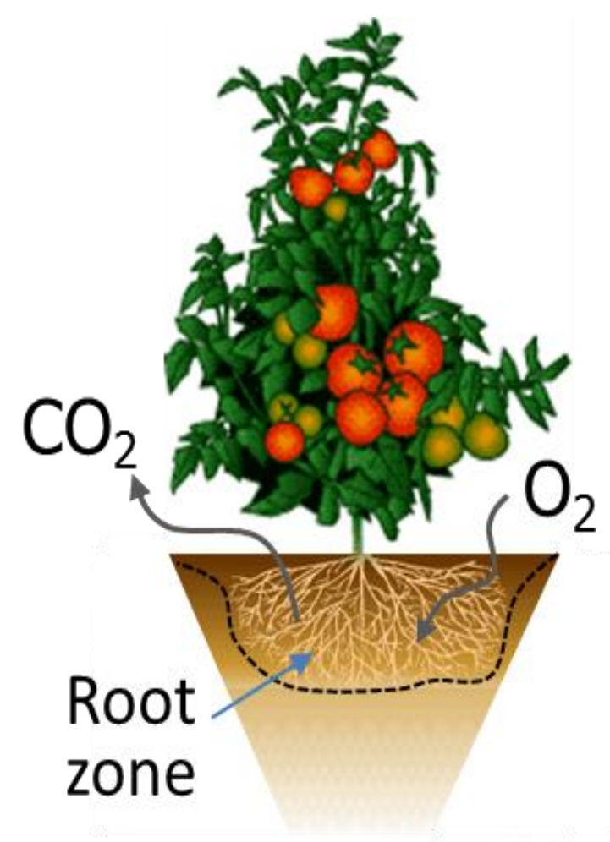
Introduction

- Growing plants in controlled volumes on the Earth and in Space (e.g., in a space station) is challenging due to limited access to essential plant needs (e.g., air, water, nutrients)
- These essential plant needs are closely linked to the growth media properties.
- Oxygen and nutrient movement in root zone occurs mainly by diffusion, and controlled by gas diffusion coefficient, D_p ($cm^2 s^{-1}$) and solute diffusion coefficient, D_s ($cm^2 s^{-1}$), respectively.

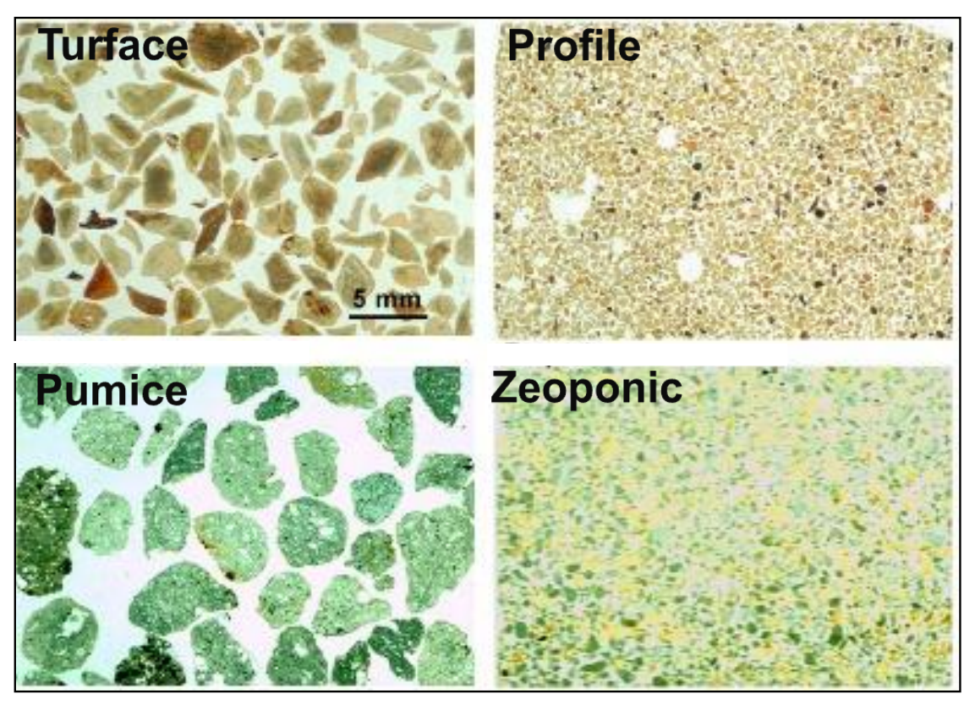


- In Space, reduced gravity plays an important but poorly understood role on water distribution in growth media, and thereby affects gas and liquid diffusion in root zone (Jones et al., 2003).
- This study presents a diffusivity-based characterization of four growth media to be used in Earth and Space environments.

Materials and Methods

- Materials and Properties:

Medium	Particle size mm	Bulk density g cm^{-3}	Total porosity $cm^3 cm^{-3}$	EGME SA $m^2 g^{-1}$
Pumice	3.2-9.5	0.36	0.85	13.9
Turface	2.0-5.0	0.62	0.75	101.4
NASA-Zeoponic	0.25-1.0	0.97	0.61	94.2
Profile	0.25-0.85	0.65	0.74	95.8



- Methods:
  - Oxygen diffusivity : One-chamber method (Taylor, 1949)

Diffusivity Models

- Oxygen diffusivity
  - Region 1:

$$\varepsilon_{in} = \varepsilon \qquad \varepsilon \le \varepsilon_p$$

$$\varepsilon_{in} = \left[\frac{\Phi_1 - \varepsilon}{\Phi_1 - \varepsilon_p}\right]\varepsilon_p \qquad \varepsilon_p \le \varepsilon \le \Phi_1$$

$$\frac{D_p}{D_0} = \alpha_1\left[\frac{\varepsilon - \varepsilon_{in}}{\Phi_1 - \varepsilon_{in}}\right]^{\beta_1} \qquad 0 < \varepsilon \le \Phi_1$$

$$\alpha_1 = \left.\frac{D_p}{D_0}\right|_{\varepsilon=\Phi_1} \qquad \beta_1 = 2 + 2.75\alpha_1$$

  - Region 2:

$$\frac{D_p}{D_0} = \alpha_1 + \alpha_2\left[\frac{\varepsilon - \Phi_1}{\Phi - \Phi_1}\right]$$

$$\alpha_2 = \left.\frac{D_p}{D_0}\right|_{\varepsilon=\Phi} - \left.\frac{D_p}{D_0}\right|_{\varepsilon=\Phi_1}$$

D_o = Gas diffuson coefficient in free air
ε_{in} = Inactive pore space ($cm^3 cm^{-3}$)

ε_p = Percolation threshold ($cm^3 cm^{-3}$)
Φ_1 = Inter-aggregate porosity ($cm^3 cm^{-3}$)
Φ = Total porosity ($cm^3 cm^{-3}$)

- Solute diffusivity
  - Determined in analogous to dielectric permittivity

$$\frac{D_s(\theta)}{D_l} = \frac{E(\theta) - E_s}{E_b - E_s}$$

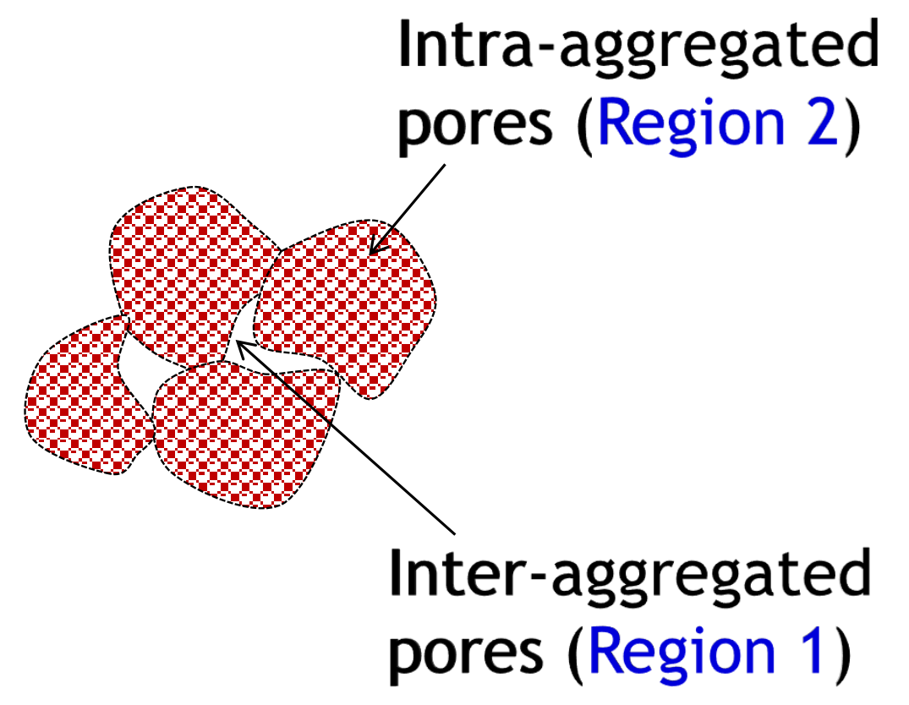
D_l = solute diffusion coefficient in free water
$E(\theta)$ = dielectric permitivity
E_s = dielectric permitivity of solid phase
E_b = dielectric permitivity of bulk water

Acknowledgement

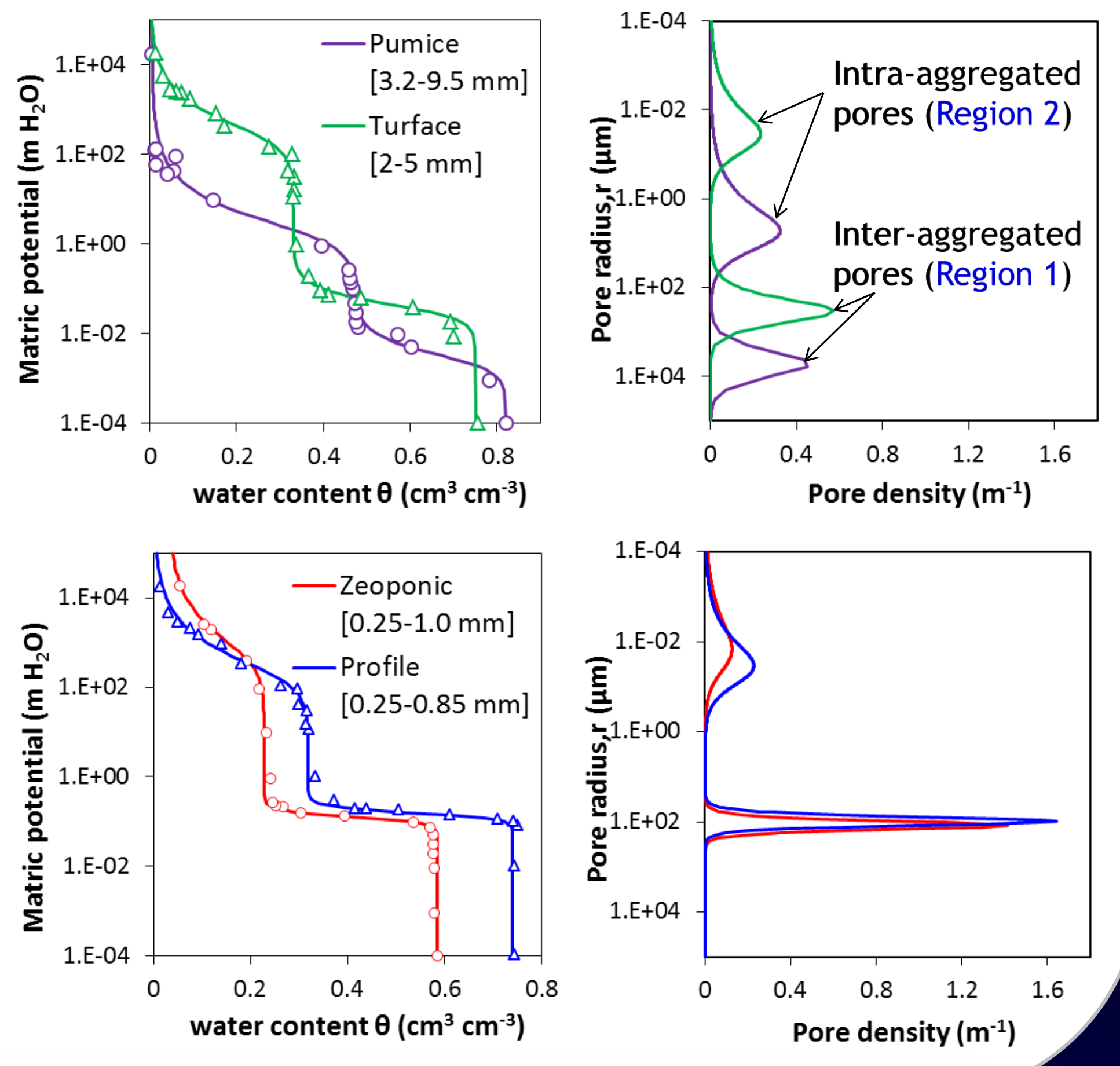
This study was part of the project Gas Diffusivity in Intact Unsaturated Soil ("GADIUS") and the large framework project Soil Infrastructure, Interfaces, and Translocation Processes in Inner Space ("Soil-it-is"), both from the Danish Research Council for Technology and Production Sciences. This study was in part supported by the Japan Science and Technology Agency (JST) in the Core Research Evolutional Science and Technology (CREST) project.

Results and Discussion

- Water Retention and Pore Size Distribution
  - All the media are bimodal and showed strong two-region characteristics

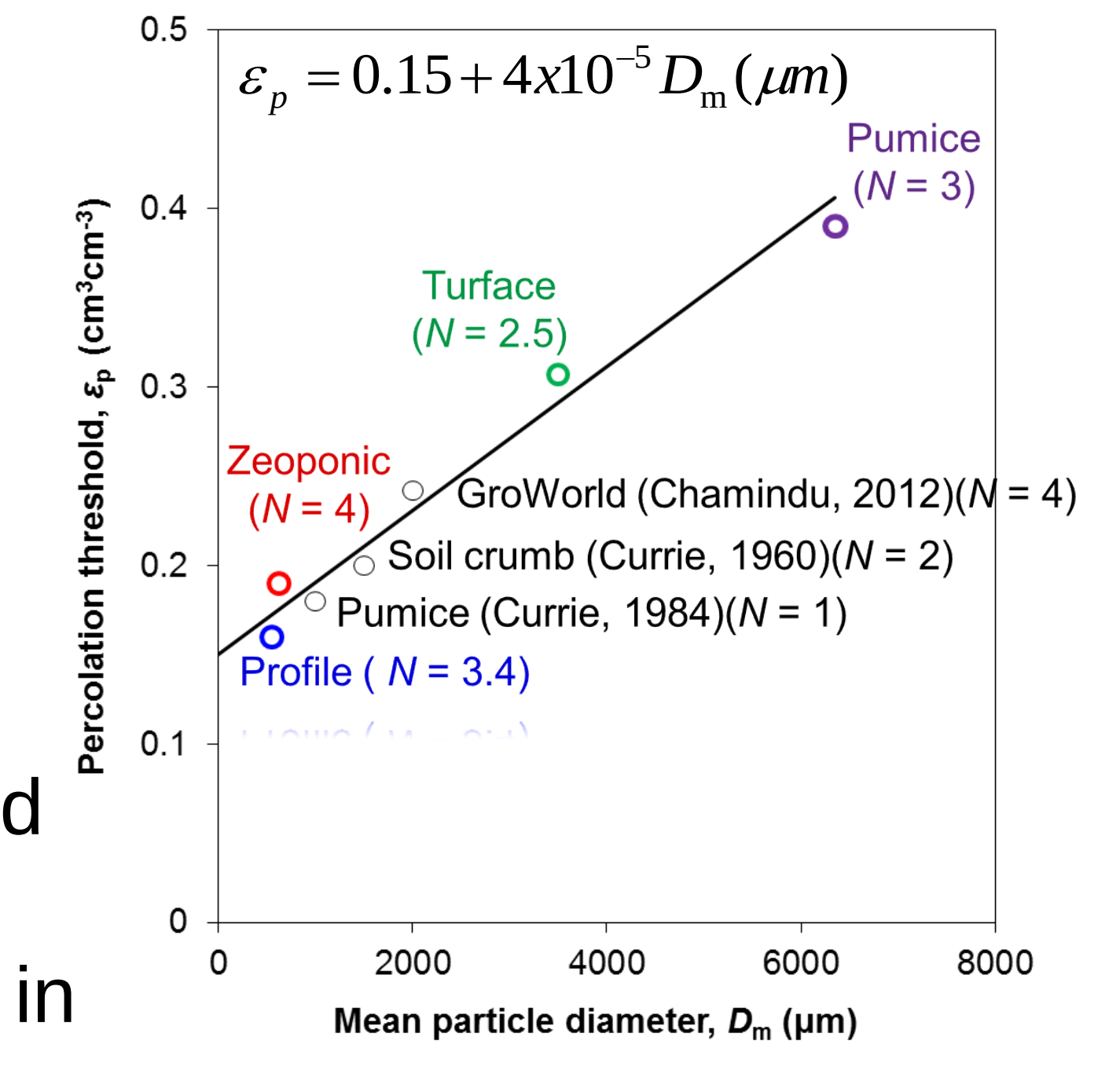


  - High total porosity and low dry bulk density provide favorable conditions to plant growth



Gas Percolation Threshold Vs. Particle Size

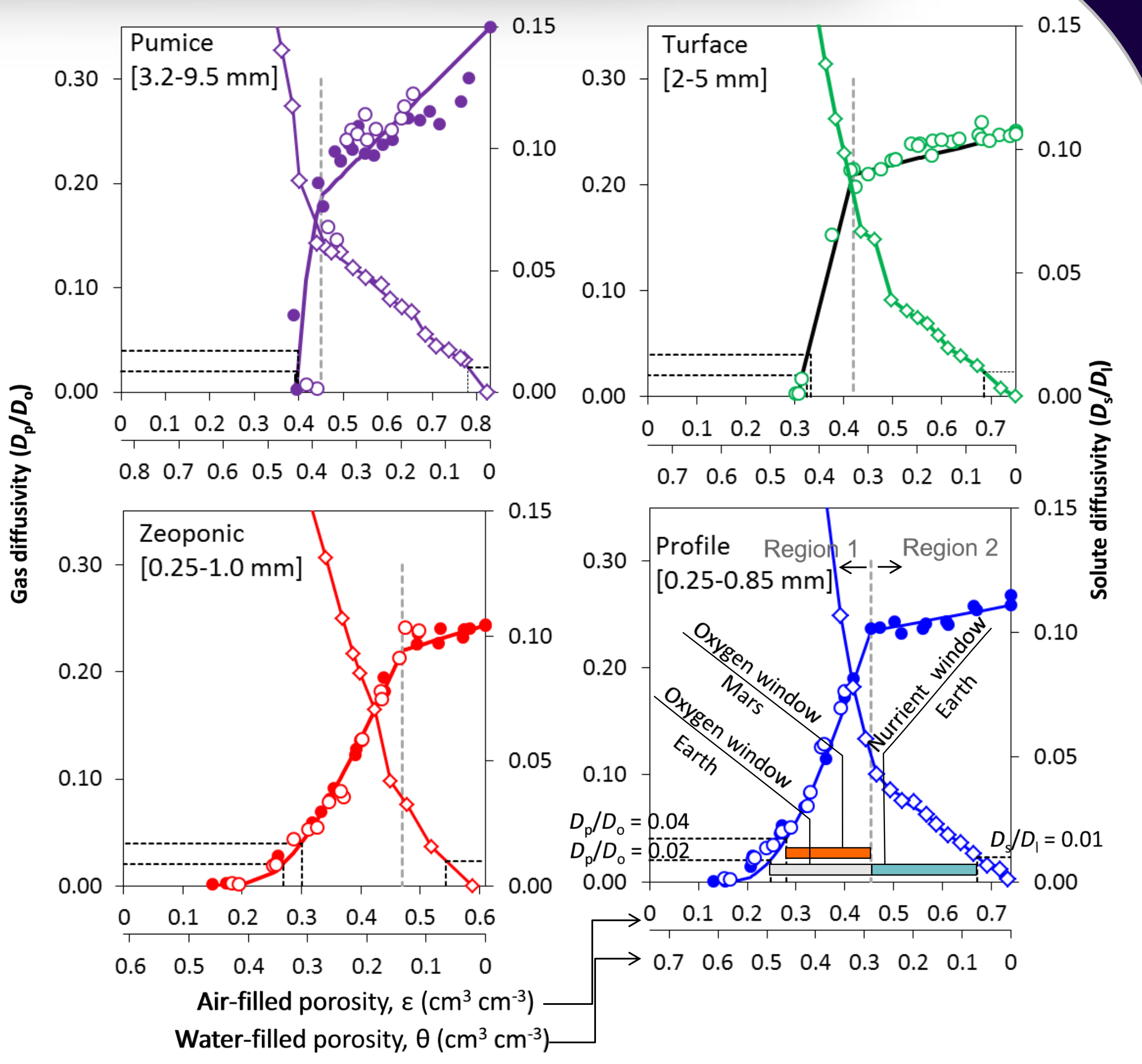
- Gas percolation threshold, ε_p ($cm^3 cm^{-3}$):
  - Air-filled pore space below which D_p remains zero due to pronounced water blockage effect.
- Particle size controls the mean pore size and also the percolation threshold thereby affects D_p.
- Strong linear relation ($r^2 = 0.98$) was observed between mean particle diameter (D_m) and ε_p, which was successfully used for predicting ε_p in later studies



(N = ratio between maximum and minimum particle size)

Critical Windows of Diffusivity

- Based on the critical (plant limiting) conditions for oxygen and nutrients in root zone *in between irrigations*, the concept of Critical Windows of Diffusivity (CWD) to evaluated media performance under critical steady state conditions.
- The CWD is defined between the region boundary and the critical diffusivity values for oxygen and nutrients.



- Critical diffusivity values:

	Oxygen	Nutrients
Earth	D_p/D_o = 0.02	D_s/D_l = 0.01
Space	D_p/D_o = 0.04	NA

- Profile showed best performance with largest windows

	Earth (1-*g*)		Space (0.37-*g*)
	Oxygen window	Nutrient window	Oxygen window
Pumice	0.054	0.331	0
Turface	0.096	0.266	0.087
Zeoponic	0.200	0.073	0.170
Profile	0.207	0.216	0.108

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