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Water vapor conductance of dry soil – Analyzing transport processes by analogy with Ohm's Law

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ABSTRACT

Soil water vapor conductance is an important part of the total water flux in the unsaturated zone, which has several significant agricultural and engineering implications. In environmental biophysics, transport processes are similar to an electrical circuit. Ohm's Law states that the electric current in a conductor is directly proportional to the applied voltage and inversely proportional to the electrical resistance of the conductor. Therefore, transport processes can be analyzed by analogy with Ohm's Law, in an integrated or macroscopic form. In this regard, water vapor concentrations are specified at the surface and in the surroundings, and the transport resistance, or conductance, is defined as the concentration difference divided by the flux density. In this study, considering that the conductance to water loss is a series of combinations of boundary layers and surface conductance, an experiment was set up in an isolated lab with constant air temperature and air pressure, in order to measure the diffusive conductance for water vapor in three dry soil types: sand, sandy loam, and silt loam. A waterproof breathable membrane with high water vapor permeability was installed between the soil samples and the water's surface, to allow water vapor move through soil samples and escape into the atmosphere. The results showed that sand, sandy loam, and loam had water vapor conductance of 0.026 $\frac{mol}{m^2.s}$, 0.027 $\frac{mol}{m^2.s}$, and 0.031 $\frac{mol}{m^2.s}$, respectively.

Key words: *Soil water vapor conductance, Environmental biophysics, Ohm's Law*

Introduction

During recent decades, water vapor transfer through soils has been considered as a critical factor, considering its substantial role in agriculture, geotechnical engineering, etc. This phenomenon has significant impact on surface-energy interactions due to its role in temperature distribution and moisture flow in soils, as well as the near-ground atmosphere system (Abuel-Naga *et al.*, 2009). The conductance to water loss is generally a series of combinations of boundary layers and surface conductance. A one cm thickness of still air has an approximate conductance of 100 $\frac{mol}{m^2.s}$, and a one cm thick layer of dry soil has a diffusive conductance for water vapor of about 0.03 $\frac{mol}{m^2.s}$. It should be noted that the 0.03 $\frac{mol}{m^2.s}$ value, reported by Campbell and Norman (2012) as the water vapor conductance of dry soil, is regardless of its physical, chemical, or mechanical properties. The following summarizes some of the studies in the literature regarding water vapor transport in soil and its applications.

Olivella and Gens (2000) developed a numerical model based on mass transfer induced by a temperature gradient, to evaluate water vapor transport in unsaturated clay soils. In order to test their model, an experimental test was conducted and the results implied that gas mobility through the soils had a direct relationship with the soils' permeability. In 2001, Kelly and Selker used a physically-based model to evaluate osmotic water vapor movement in different unsaturated soils, including clay loam and medium sand. Additionally, they developed a set of water vapor transport equations under isothermal conditions. In another study, Dobchuk *et al.* (2004), conducted a study in order to estimate water vapor diffusion mechanisms in waste rock. Using both numerical and experimental studies, they demonstrated the significant role of water absorption in transient water vapor flux.

In 2006, a study was conducted by Sakai *et al.* in order to measure water and water vapor movement in a cold, dry, sandy column, using HYDRUS-1D code and the Philip and de Vries model (Philip and de Vries, 1957). They demonstrated significant water vapor transfer rates in unsaturated soils, while the initial water content was relatively low. Moreover, using the HYDRUS-1D software package, Saito *et al.* (2006) investigated the relationship between water vapor and heat in fine sandy loam soils. The results implied a strong relationship between soil water dynamics and soil temperature. In addition, the significant role of water vapor in the prediction of soil water content, as well as its temperature, was demonstrated.

In 2015, by developing a numerical model based on the heat and mass transfer mechanisms, Teng *et al.* revealed the significant water vapor migration in unsaturated frozen soils with different hydraulic properties. Although they implied migration differences with the different soil types, the results demonstrated the direct relationship between temperature gradient, initial water content, and water vapor flux percentage. In a field experiment, using the micro-lysimeters method, isotopic mass balance, and the Rayleigh equation, Wu *et al.* (2017) studied water vapor exchange under plastic mulch films. To evaluate this exchange, a combined soil consisting of loam at the top, and sandy loam at the bottom was used. The results showed a relatively high water vapor exchange and soil evaporation through the mulch holes.

Using a series of one-side freezing experiments, Bai *et al.* (2018) investigated the moisture migration of a coarse-grained soil, including silty clay and standard sand. The results of this experimental study revealed that the initial water content of the soil and water vapor migration were inversely related. Moreover, He *et al.* (2018) established a numerical model for liquid water-water vapor-heat migration through unsaturated frozen soils, based on the seepage theory. The results showed that in the soil specimens, the total volumetric water content increased significantly, by vapor migration. Using an experimental study, Gao *et al.* (2018), examined the effects of fines content on water vapor and the frost capacity of a coarse-grained soil. They revealed the significant impact of water vapor flux on frost heave.

The literature review showed that previous studies have provided a wide range of experimental and numerical methods to study water vapor transfer dynamics in various soil types. The present study seeks to find the diffusive conductance for water vapor in three dry soil types including sand, sandy loam, and silt loam, with different bulk densities, by conducting an experimental study in an isolated lab at Washington State University. This study implements transport equations by analogy with Ohm's Law, as a novel approach, to evaluate the 0.03 $\frac{mol}{m^2.s}$ value reported in the literature as the soil's water vapor conductance (Campbell and Norman, 2012).

Materials and Methods

Theoretical Formulation

Several equations exist that describe the rate of mass or energy transportation in different media. The most familiar ones include Darcy's Law, Fourier's Law, Newton's Law, and Fick's Law, which are used to calculate fluid flow in a porous medium, heat transport, viscosity for momentum transport, and diffusive transport of materials, respectively. According to Fick's Law, the transportation of materials is the proportion of the flux density and concentration for a diffusive substance, which is described as:

$$F_j = \frac{F_j'}{M_j} = -\hat{\rho} D_j \frac{dC_j}{dZ} \quad .. (1)$$

where *j* is for gas, F_j' is the flux density (kg/m^2.s), M_j is the molar mass of gas (g/mol), *p* is the molar density of air (mol/m^3), D_j is the molecular diffusivity

(m^2/s), C_j is the concentration (kg/m^3), and dC_j/dz is the concentration gradient. According to Equation (1), the heat flux density is defined as a proportion of the thermal conductivity and temperature gradient. Hence, the heat flux density is described as:

$$H = -\hat{\rho} c_p D_H \frac{dT}{dZ} \quad .. (2)$$

where H is the heat flux density (W/m^2), C_p is the specific heat of air at constant pressure (Jmol.C), D_H is the thermal diffusivity (m^2/s), and dT/dz is the molecular diffusivity (C/m) in a substance with the thermal conductivity of k ($^{W}/_{m.K}$).

As heat transportation through geomaterials and microorganisms is similar to an electronic circuit, Ohm's Law can be used in this system. Considering the fact that the heat gradient measurement on a microscopic scale is arduous, the transport equations can be replicated according to Ohm's Law. By defining the conductance as the concentration difference divided by the flux density, the Ohm's Law is described as:

$$E = g_v(C_{v(air)} - C_{v(water)}) = \frac{C_{v(air)} - C_{v(water)}}{r_v} \quad .. (3)$$

$$g = \hat{\rho} \frac{D_j}{\Delta Z} \quad .. (4)$$

where g is the conductance ($mol/m^2.s$), r is the resistance ($m^2.s/mol$), and Cv is the vapor concentration. The subscript v stands for vapor.

To calculate the evaporation rate, it is necessary to know the vapor concentration at the evaporating surface, which acts as the interface between the liquid water and the gas phase. If the surface is free water, the vapor concentration at this interface is the saturation vapor concentration at surface temperature. If the surface is not a free water surface, then it is expected that the surface has a humidity of less than 1.0, and a vapor concentration of less than the saturation concentration. The equation to calculate this concentration is described as:

$$C_{vs} = h_{rs} \frac{e_s(T_s)}{pa} = h_{rs} C_v(T_s) \quad .. (5)$$

where C_{vs} is the saturation vapor concentration, h_{rs} is the relative humidity of the interface between the liquid and the gas phase, e_s is the saturation vapor pressure (kPa), Ts is the temperature (K), and p_a is the atmospheric pressure (kPa).

In the case of heat exchange through soils, Equation (5) can be modified for $C_{v(air)}$ and $C_{v(water)}$, to represent the vapor concentration in the gas and in the liquid phase, respectively. The modified equation is shown in Equations (6) and (7).

$$C_{v(water)} = \frac{e_s(T_{water})}{pa} \quad .. (6)$$

$$C_{v(air)} = \frac{e_a}{pa} \quad .. (7)$$

where e_a is the ambient vapor pressure of the air (kPa). Since, in normal conditions, the air is not at the saturation level, the relative humidity term is used to define the ambient vapor pressure. In order to calculate e_a, Equation (8) is used:

$$e_a = h_r e_s(T_a) \quad .. (8)$$

where h_r is the relative humidity and T_a is the ambient temperature (K). As mentioned earlier, the heat and vapor flux could be exchanged from organisms' surfaces and the surrounding environment, between plant canopies and the atmosphere, or between soils and the air. In order to calculate this flux rate, the surface temperature, along with the water potential of the liquid phase, should be measured. Since the boundary layers and surface conductance are in series, the total conductance in soils can be calculated as:

$$g_v = \frac{1}{\frac{1}{g_{v(membrane)}} + \frac{1}{g_{v(soil)}} + \frac{1}{g_{v(air)}}} \quad .. (9)$$

where the $g_{v(membrane)}$, $g_{v(soil)}$, and $g_{v(air)}$ are the conductance of the interface, soil, and air, respectively.

Soil Types

Three different soil types were investigated in this experiment, and since the value reported in the literature was regardless of the physical, chemical, or mechanical properties of the soil, only the bulk densities of the soils were measured. It should be noted that bulk density is not an intrinsic property of the material; it can change depending on how the material is handled. The soil types used in this study, along with their bulk densities are presented in Table 1.

Membrane

A waterproof breathable membrane, manufactured by eVent FABRICS, with high vapor permeability

Table 1. Soil types and their bulk densities.

Soil Type	Bulk Density (g/cm^3)
Sand	1.574
Sandy Loam	1.555
Silt Loam	1.268

was used in this study (Fig. 1). This waterproof breathable membrane is covered in billions of microscopic pores, giving the laminate its waterproof-breathable properties. Water droplets are too large to pass through the membrane, but the pores let small water vapor molecules escape. The membrane used in this study had 30 m of water column resistance, 10,000 gm^2 of breathability, and 1.7 *10^{-3} m^3/min of air permeability.

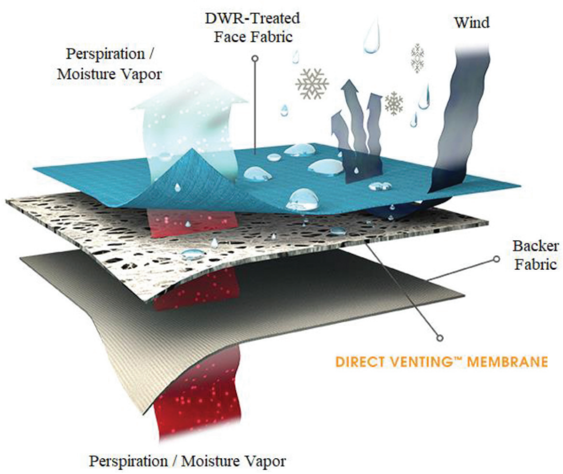

Fig. 1. The waterproof-breathable membrane.

Leaf Porometer

In order to measure the vapor conductance of the membrane, an SC-1 Leaf Porometer, manufactured by the Meter Group Company, was used. The Leaf Porometer is a device used to measure the stomatal conductance in leaves. This device is able to measure the conductance with the accuracy range of 0-1000 mmol/m^{2}s.

Em50 Data Logger

For measuring the temperature and relative humidity in the environment, an Em50 data logger, manufactured by the Meter Group Company, was used. The Em50 is a self-contained data logger, built to power, read, and log data from five built-in sensors. The Em50 can store more than 36,000 data scans. A scan includes the logger name, the date and time, along with measurements from each of the five ports.

Thermal Anemometer

In order to measure the wind speed above soil surfaces, a thermal anemometer, manufactured by the Meter Group Company, was used. Thermal anemometers use a very fine wire, or element, heated to a temperature above ambient. Air flowing over it has a cooling effect. As the electrical resistance of most metals is dependent upon the temperature of the metal, a relationship can be obtained between the resistance of the wire and the flow velocity. The voltage output from these anemometers is, thus, the result of some sort of circuit within the device trying to maintain the specific variable (current, voltage, or temperature) constant. Hot-wire anemometers, while extremely delicate, have extremely high frequency-responses and fine spatial resolutions, compared to other measurement methods.

Experiment Setup, Results and Discussion

For this experiment, three containers were used, which contained water and the soil samples. As illustrated in Figure 2a, the containers were initially filled with water; then the waterproof-breathable membranes were installed above the water surface. The soil samples were dried in an oven for 24 hours. Afterward, a three cm thick layer of dry soil was placed above each membrane and slightly compacted to reach the compactness values mentioned in Table 1. The water level in the containers was two cm below the membrane, and in the distance between the two, saturation conditions were assumed. The membranes were glued to the containers in a way that water vapor could escape into the atmosphere only through the soil. Before installing the membranes, the $g_{v\text{-}membrane}$ was measured using the porometer, and a value of 0.610 $\frac{mol}{m^2.s}$ was obtained. Since the experiment was performed in an isolated lab at Washington State University, Em50 data showed that the temperature and relative humidity were constant during the experiment. In order to increase the boundary layer conductance over soil surfaces, a fan was used, which created a wind speed of 1.9 m/s over silt loam, 1.8 m/s over sandy loam, and 1.7 m/s over the sand surface (Figure 2b). Using an accurate scale, the containers were weighed at the start of the experiment, and 24 hours later they were weighed again to measure the water loss. The EM50 Datalogger data showed that during the experiment T, h_r, e_a, e_s (T_{water}), $p_{a\ (kPa)}$, $C_{v(water)}$, and $C_{v(air)}$ were constant. The values of these parameters are presented in Table 2.

Water vapor moves through unsaturated soils as a result of either thermal gradients or concentration gradients. The results, as are presented in Table 3, showed that the water vapor conductance of the three soil types were close to the values suggested by Campbell and Norman (2012). But in comparison, silt loam with finer soil particles, showed a higher conductance, compared to sandy loam and sand. Sandy loam, with a bigger particle size compared with sand, showed a higher gv value as well.

In similar studies, researchers also investigated the impact of temperature on soil water vapor conductance, and concluded that increasing temperature increases the total quantity of water vapor diffusing through the soil in response to concentration gradients. Even in dry soils, some moisture movement takes place in vapor form and plays an important role in soil water regimes (Jackson, 1963; Onchukov *et al.*, 1972). Moreover, early studies demonstrated that moisture movement in response to a thermal gradient through an unsaturated soil occurs mainly in the vapor phase (Taylor and Cavazza, 1954; Rollins, Spangler, and Kirkham, 1954; Kuzmak and Sereda, 1957; Matthes and Bowen, 1963).

In addition to the findings of this study, an understanding of gas transport in unsaturated media is important for the evaluation of soil aeration from the atmosphere to the soil. Considering the fact that roots generally cannot get enough O_2 from leaves, soil aeration is critical for plant root growth. Because of density and viscosity differences between air and water, air conductivities are generally an order of magnitude less than water or hydraulic conductivities in the same material; gas diffusive fluxes are generally much greater than those of water, making gas molecular diffusion coefficients about four orders of magnitude greater than those of water (Rathfelder *et al.*, 1995). This issue highlights the importance of studying gas conductance in the soil medium, including soil water vapor conductance.

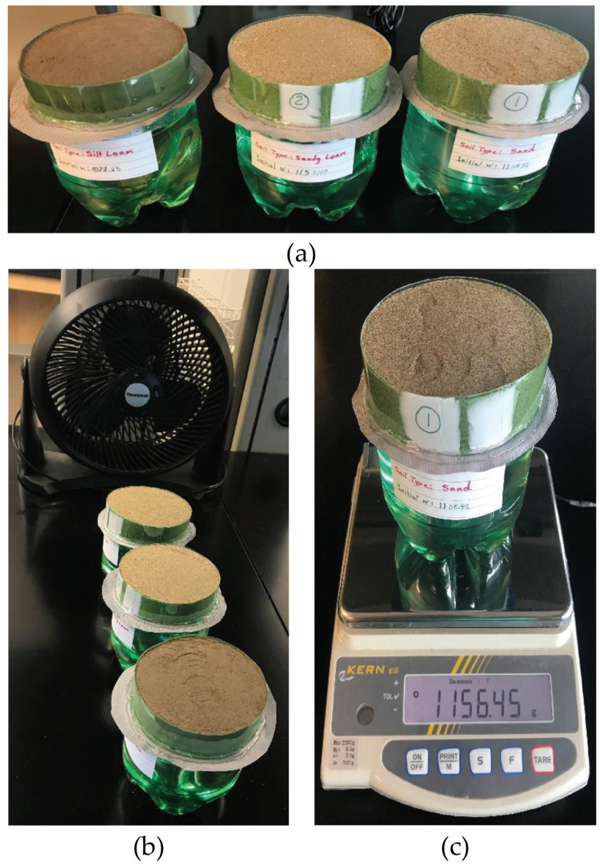

Fig. 2. (**a**) Soil samples in containers, (**b**) increasing the boundary layer conductance over the soil surfaces.

Table 2. Constant parameters during the experiment.

Parameter	T (°C)	h_r	e_a	e_s (T_{water})	pa (kPa)	$C_{v(water)}$	$C_{v(air)}$
Value	22.2	0.291	0.77115	2.65	101	0.02623	0.00766

Table 3. The g_v values for different soil types in this experiment.

Soil Type in the Container	Initial Weight (g)	Final Weight (g)	$g_{v(soil)}$ ($\frac{mol}{m^2.s}$)
Sand	1158.42	1156.44	0.026
Sandy Loam	1153.4	1151.32	0.027
Silt Loam	1077.25	1074.90	0.031

Conclusion

Considering the important implications of soil water vapor conductance in agriculture and engineering, this study investigated the diffusive conductance for water vapor (g_v) in sand, sandy loam, and silt loam in an experimental study. Equations derived by analogy with Ohm's Law were used to calculate the g_v, considering that the conductance to water loss was a series of combinations of boundary layers and surface conductance. Finally, the g_v values for sand, sandy loam, and loam were found to be 0.026 $\frac{mol}{m^2.s}$, 0.027 $\frac{mol}{m^2.s}$, and 0.031 $\frac{mol}{m^2.s}$, respectively, which shows that silt loam, with finer soil particles, had a higher g_v value, compared with the other two soil types. Similarly, sandy loam, with bigger particle sizes relative to sand, showed higher water vapor conductance. For future extension of this research, it is recommended to use more soil types, with different chemical, physical, and mechanical properties, to obtain a range of g_v values under different environmental conditions.

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