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HYSTERETIC BEHAVIOUR OF THE SOIL THERMAL PROPERTIES BASED ON WETTING AND DRYING CYCLES

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Palabras clave: water content, silt loam soil, dual needle sensor, heat pulse method

RESUMEN. *El objetivo de este trabajo es explorar la influencia del comportamiento histerético en el transporte de calor, estudiando las propiedades térmicas de un suelo franco limoso en condiciones de laboratorio. Para ello, se utilizó un sensor térmico de doble aguja. Para la caracterización hidrodinámica se utilizaron minitensiometros y sondas de FDR, y un WP-4 para caracterizar la zona más seca de la curva. Las propiedades térmicas mostraron una relación lineal con los contenidos hídricos. Se observó un modelo de histéresis espacio-temporal, en términos de propiedades térmicas. Este comportamiento histerético podría estar relacionado con factores como los diferentes grados de saturación, los cambios en la temperatura y su influencia en el transporte de calor, y la geometría de la lámina de agua alrededor de las partículas.*

ABSTRACT. *The aim of this research is to explore the influence of hysteresis on heat transport in soils under experimental laboratory conditions. Soil thermal properties were determined using a dual-needle sensor. To characterize [$\theta(\psi)$] function minitensiometers, WP-4 Dewpoint potentiameter, and FDR probes were used. Cv and λ showed positive linear correlation with soil volumetric water content. The divergences in α values could be explained by relationship between water content and porous media diameter, and the spatial interaction between heat transfer and soil moisture. A spatial-temporal hysteresis pattern was observed in thermal properties. Hysteretic behavior could be related with factors as: degree of saturation, the influence of temperature difference on the heat transport, and the geometry of the water layer around the particle.*

1. INTRODUCTION

Characterization soil physical data are required in many field and laboratory experiments. Some kinds of data are related with thermal properties and heat transport. Thermal properties in soils are: the thermal conductivity (λ, W·m^{-1}·C^{-1}), the soil volumetric heat capacity (C_v, MJ·m^{-3}·C^{-1}), and the thermal diffusivity (α, mm^2·s^{-1}), combining both describes the rate of transmission of temperature change within the soil (Shiozawa and Campbell, 1990; Bristow et al., 1994).

Soil thermal properties are influenced, among other variables, by particle size distribution, volumetric water content and bulk density. The particle size and its distribution also have an effect on the manner in which the moisture is held (Singh and Devid, 2000). Soil water content has an important role in determining soil thermal properties, due to the conduction through soil is largely electrolytic (Van Rooyen and Winterkorn, 1957). Other soil physical properties have a lesser effect, whether it is compared with the water content effect (Al Nakshabandi and Kohnke, 1965), and bulk density.

On the other hand, in laboratory conditions thermal properties largely should be influenced for drying and wetting processes driven by water potential differences, being the relationship between water potential and water content a consequence of wetting and drying history (Hillel, 1980). This effect of a non-unique water-retention curve, i.e. the soil water hysteresis, is relevant for the gas-phase continuity, which influence on soil thermal properties. The hysteresis phenomenon has been well documented in the literature beginning with the work of Haines (1930), and followed by other authors, such as Philip (1964); Poulovassilis and Childs (1971), Kutilek and Nielsen (1994), and Bristow (1998) who related thermal properties with water potentials.

The purpose of this research is to explore the influence of hysteresis as one of the decisive factors in causing differences on heat transport. Thus, the aim of our work is divided in two different directions; (i) to measure and to analyze soil thermal and hydrodynamic properties, and (ii) to explore the impacts of hysteresis on soil thermal properties under experimentally controlled conditions.

2. METHODOLOGY

A sampling plot was located in Can Solé Road, sited in the Llobregat delta plain (Northeast of Spain). The samples were obtained between the surface and 30 cm below the surface. Particle size distribution, bulk density, total organic carbon content, and calcium carbonate content were measured for each sample.

Measurements of thermal-hydrodynamic properties on soil columns constructed specifically for this experiment were made. Fig. 1 shows, the column device was developed using methyl methacrylate component (25 cm diameter, 35 cm large), with a inner slope of 3º. The slope allowed a well drainage of the gravitational water content, avoiding ponding. To obtain a correct wetting process from the bottom of the column, the device was connected to a separatory funnel. The instrument worked as a water deposit. To obtain a well-defined drying cycle, we used the communicating vessel principle.

The lower levels of the column were refilled with gravel (4 to 8 mm of diameter) and sand particle size (250 to 1000 μm). . Both layers were allowed to reach a necessary water level in the column, and a homogeneity wetting process of the sample, respectively. A separatory funnel provided a moderate water potential gradient into the soil column. Several sensors were placed for two different levels (a and b), and thus to control two different moisture scenarios.

An SH-1 small dual-needle sensor (Decagon Devices Inc.) was employed to determine thermal properties of the soil column. The SH-1 thermal sensor combined with KD2-Pro (Decagon Devices, Inc.) reader-logger used the heat pulse methodology to yield reliable and accurate soil α and λ estimations. C_v was determined from thermal conductivity and diffusivity data, following the expression:

$$C_v = \frac{\lambda}{\alpha} \quad (1)$$

To determine the volumetric water content (θ) and the water potential (ψ), the soil column was monitored with two EC-5 frequency domain probes (Decagon Devices Inc.) and two T-5 minitensiometer (UMS GmbH). The sensors were placed in pairs (one T5 and one EC5 at the same level) for two different levels (a and b). A Campbell Scientific CR-850 and Decagon Devices EM-50 data-loggers were used to collect the data. [$\theta(\psi)$] data from saturation to -83 kPa with minitensiometer (Vandervaere et al., 1997; Nahlawi et al., 2007) were measured. However, to measure the dry end of the water retention curve, a WP-4 device (Decagon Devices) was used (Brye, 2003; Thakur et al., 2005). Both data sets were used to estimate the water retention curve during the drying process.

3. RESULTS AND DISCUSSION

The studied soil from Can Solé Road was classified as silt loam textural class (USDA), with a particle size distribution for silt content always higher than 60%, mean sand content about 34%, and mean clay content about 4%. Mean bulk density was 1.47 $g \cdot cm^{-3}$ and total porosity 45%. Mean total organic carbon content was about 3.1%, and mean calcium carbonate content was 40.3%.

A soil water retention curve (Fig. 2) was obtained by fitting the observed data to the Van Genuchten equation (1980). The water retention curve showed a volumetric water content close to saturation at approximately 0.45 $cm^3 \cdot cm^{-3}$. The values of water content for field capacity and permanent wilting point were 0.20 and 0.09 $cm^3 \cdot cm^{-3}$, respectively. The van Genuchten model fit the estimated water retention data to observed data with $r \cong 0.98$ and $p \leq 0.01$. Estimated water content values were in the range of the values found in the literature for these types of soils (Cameron, 1978; Gupta and Larson, 1979; Martínez-Fernández et al., 2003).

Soil wetting curves are presented in Fig. 3. The two curves showed a well-defined wetting process. For rising the capillarity between the a and b points (separated by 12 cm) were spent 40 hours, with large differences in the water content between both levels. When the probe a (upper level) started to increase the moisture values (from 0 initial) probe b presented values at about 35% of water content. These differences decreased to 20% when the probe b (lower level) reached saturation. At this point, both levels reached steady-state conditions. In terms of water potential, the observed data was -1.41 kPa for level a, and close to 0 kPa for level b. The temperature line indicates the daily temperature cycles for the observed period. Note that exists a slight decreasing on the soil temperature (between 260 to 340 hours of observation), this fact was due to a decrease in the room temperature. This involved a reduction of the temperature of the water content inside the column device, affecting to the evaporation demand.

Fig. 4 and 5, shows the influence of water content on the thermal properties for the soil sample using the level a dataset. The thermal dataset was obtained simultaneously with the wetting process in the soil sample..

Thermal conductivity (Fig. 4) and thermal diffusivity (Fig. 5) *versus* volumetric water content were directly observed data. However, the volumetric heat capacity (Fig. 6) as a relation of the function $\alpha(\lambda)$ was calculated. In Fig. 4, the positive relationship between the silt loam soil λ and water content (Singh and Devid, 2000), suggests that the most significant correlation when soil moisture was higher 20% $vol \cdot vol^{-1}$ ($r = 0.987$ $p \leq 0.01$). The largest increase in λ occurred during the wetting processes range. The thermal properties (λ and α), both showed a nearby steady-state scenario when the volumetric water content was close to 25% $vol \cdot vol^{-1}$, assuming a constant slope (Nakshabandi and Kohnke, 1964; Bristow, 1998), being the water content at level b near to saturation (Hadas, 1974; Nobre and Thomson, 1993). Several time steps were evident during the wetting process where the soil moisture showed a slight decreasing (see grey line in Fig. 4), at these points the thermal conductivity values were different for the same water content data. This fact elucidates a small hysteretic behavior, related with the manner as the pore water content was drained and refilled again. Fig. 5, shows the relationship between thermal diffusivity as a function of water content for a silt loam soil. Thermal diffusivity and thermal conductivity showed a similar behavior, also with a constant slope between 10% to 20% vol·vol^{-1} of water content, and steady-state conditions when soil moisture was over 20% vol·vol^{-1}. These different scenarios could be related to severe vapor transfer before to reach a high soil moisture, i.e. the fast increase of the α values between 10% and 20% vol·vol^{-1} of water content.

Variation of volumetric heat capacity for a silt loam soil as a function of water content is shown in Fig. 6. The results showed an increase of the volumetric heat capacity as soil moisture increased. C_v varied linearly with water contents among air-dried to 0.1 m^3·m^{-3}, which is consistent with equation (1). The slope of the curve is nearly the same as that obtained in Fig. 4 where the thermal conductivity curve was analyzed. Volumetric heat capacity did not increase uniformly with increasing water contents (Fig. 6). Initially, from 0.1 m^3·m^{-3} volumetric heat capacity increased rapidly, just that the contact among the particles was improved by the film water content (Abu-Hamdeh, 2003). However, the increase of the measurements was slower than expected.

In Fig. 7a, 7b and 7c, we show the wetting and drying cycles related to thermal properties data, which was observed for the studied soil (i.e., 34% sand, and 4% clay). All thermal properties in Fig. 7 were determined for the same spatial-temporal scenario. Good agreement, in general, existed between the thermal conductivity measurements and the soil hysteretic behavior (Fig. 7a), which was subject to drying and wetting cycles (Bristow, 1998; Bristow et al., 2001). Thermal conductivity measurements at the end of the wetting process showed a linear increase with the soil water contents. Whereas, during the drying cycle an unexpected reaction increased the values of the soil thermal conductivity. When the water in soil began to decrease, then the thermal conductivity started a rapid decrease, in parallel to the wetting process.

Differences in temperature fluxuation between the wetting and drying cycle confounded the data. A 12 degree Celsius change in the soil temperature (due to changes in room temperature) during the drying process controlled certain divergences in the thermal dynamic behavior, as is the case of the Fig. 7.

On the other hand, the temperature oscillation during the wetting process was negligible, maintaining steady-state conditions all times. Although, several studies carried out by De Vries (1963), Campbell and Jungbauer (1994), Campbell and Norman (1998) about the effects of the temperature on the thermal properties, maintain that in a moist soil at room temperature 10% to 20% of the total heat transport is as latent heat through the soil pores. This portion of the heat transport is strongly temperature dependent, roughly doubling for each 10°C temperature rise. Therefore, the variable temperature produced a small effect on the thermal conductivity when the temperature decreased 12ºC, such that the heat transport was reduced (see dot circles in Fig. 7a).

Fig. 7b and 7c show the influence of water content in volumetric heat capacity and thermal diffusivity, respectively. Volumetric heat capacity (Fig. 7b) presented a well-defined hysteresis process, and the variations of the temperature during the drying curve did not affect either cycle.

On the other hand, Fig. 7c showed the greatest differences between both moisture cycles. Thermal diffusivity increased as water content was increased in soil. Conversely, during the drying cycle, , the values of α showed a constant increase. The relationship between volumetric water content and porous media diameter as well as the spatial interaction between heat transfer and soil moisture may explain these divergences in α values.. The most significant factor is the thickness and geometry of the water layer around the particle (Al Nakshabandi and Kohnke, 1964), which determined the heat transfer in the system. λ and especially α values would depend highly on the manner in which the best conducting mineral particles were interconnected by the less conducting water phase, and were separated by the poorly conducting gas phase (Koorevaar et al., 1983). Therefore, the heat transport in the soil took place mainly through the narrow points of contact between the particles. The water around contact points formed very effective "bridges" for conduction of heat. However, a thin film formed around the soil particles during both processes, having different λ and α values for the same water content, such as were shown in Fig. 7a and 7c. Also, the variations in the volume of the air fraction (Oschner et al., 2001) explained much of the variation in thermal diffusivity data rather than other variables, just that in driest measures for this soil the relationship was not typically linear.

Although, we used dionized water to carry out the experiment, there could exists a slight influence of few dissolved solids on suction causing changes in surface tension of the water content during the drying process (Case and Welch, 1979). This would indicate differences among the film water around the particles. Also, the variations of the temperature would influence the rate of latent heat, yielding significant differences in the gas phase, and controlling the different scenarios which occurred in both cycles. Therefore, we could assume that the values of thermal properties varied according to the thermal state of the system.

4. CONCLUSIONS

A laboratory-scale study of heat flow and water was conducted in Technical University of Catalonia. Soil thermal properties and soil water contents were measured at two depths under different soil moisture regimes. A soil column device presented a well-defined soil wetting process, yielding an acceptable observed thermal and hydrodynamic data set. A slow capillary rise in the porous media favored a not collapse of the porosity by the air-entry, and therefore a direct contact between the thermal sensors and soil. Thus, the special design of the column device presented a higher effectiveness.

The experiment produced a unique and comprehensive data set useful for quantifying the spatial-temporal dynamics of λ, C_v and α based on several moisture levels. Thermal properties showed an acceptable relationship with water content, showing a linear relationship.

Analysis of soil thermal properties provided a complete picture of a spatial-temporal hysteresis pattern in soils. The influence of the hysteretic behavior on soil thermal properties, shown in Fig. 7a, 7b and 7c, was related with several important factors: degree of saturation, temperature changes and its influence on the heat transport, and the geometry of the water layer around the particle. Further research is planned for determining the effect of additional variables (e.g. the effects on compacting and water potential) on thermal hysteretic behavior.

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REFERENCES

Abu-Hamdeh N.H. 2003. Thermal properties of soils as affected by density and water content. *Biosystems Engineering*, 86(1):97-102.

Al Nakshabandi G., Kohnke H. 1965. Thermal conductivity and diffusivity of soils as related to moisture tension and other physical properties. *Agricultural Meteorology*, 2: 271-279.

Bristow K.L., White R.D., Kluitenberg G.J. 1994. Comparison of single and dual probes for measuring soil thermal properties with transient heating. *Australian J. Soil Research*, 32: 447-464.

Bristow K.L. 1998. Measurement of thermal properties and water content of unsaturated sandy soil using dual-probe heat-pulse probes. *Agric. Forest. Meteorol.*, 89: 75–84.

Bristow K.L., Kluitenberg G.J., Goding, C.J. Fitzgerald T.S. 2001. A small multi-needle probe for measuring soil thermal properties, water content and electrical conductivity. *Computers and Electronics in Agriculture*, 31: 265-280.

Brye K.R. 2003. Long-term effects of cultivation on particle size and water-retention characteristics determined using wetting curves. *Soil Science*, 168, 7: 459-468.

Cameron D.R. 1978. Variability of soil WRC and predicted hydraulic conductivities on a small plot. *Soil Sci.,* 126, 6:364-371.

Case C.M.; Welch A. 1979. Pore size distribution, suction and hysteresis in unsaturated groundwater flow. *J. Hydrol.*, 43, 99-120.

Campbell G. S., Jungbauer Jr. J.D., Bidlake W.R., Hungerford R.D. 1994. Predicting the effect of temperature on soil thermal conductivity. *Soil Sci.* 158:307-313.

Campbell G. S., Norman J. M. 1998. *An Introduction to Environmental Biophysics*, 2nd Ed. Springer Verlag, New York.

DeVries D.A. 1963. Thermal properties of soils. In: W.R. van Wijk (Editor), *Physics of plant environment*. North-Holland Publishing Co., Amsterdam, pp. 210-235.

Gupta S.C., Larson W.E. 1979. Estimating soil water characteristic from particle size distribution, organic matter percent, and bulk density. *Water Resour. Res.*, 15: 1633-1635.

Hadas A. 1974. Problems involved in measuring the soil thermal conductivity and diffusivity in a moist soil. *Agric. Meteorol*., 13: 105-113.

Haines W. 1930. Studies in the physical properties of soil: V. The hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith. *J. Agric. Sci.* 20, 97–116.

Hillel D. 1980. *Fundamentals of Soil Physics*. Academic Press, New York, 413 pp.

Koorevaar P., Menelik G., Dirksen C. 1983. *Elements of soil physics*. Develop. in soils science 13. Elsevier, New York, 230 p.

Kutilek M., Nielsen D.R. 1994. Soil hydrology. *Catena*, Cremlingen-Desdedt, Germany. 370 p.

Martínez-Fernández J., Ceballos Barbancho A., Casado Ledesma S., Morán Tejada C. 2003. Estabilidad temporal de la humedad edáfica bajo diferentes condiciones ambientales mediterráneas y de uso del suelo. In: J. Álvarez-Benedí, P. Marinero (Editors), *Estudios de la Zona No Saturada del Suelo*, 7: 77-82.

Nahlawi H., Bouazza A., Kodikara J. 2007. Surface water infiltration in a 1-dimensional soil-geotextile column. In: J. Ameratunga, B. Taylor & M . Patten, *Proceedings of the 10th Australia New Zealand Conference on Geomechanics*.

Nobre R.C.M., Thomson N.R. 1993. The effects of transient temperature gradients on soil moisture dynamics. *J. Hydrol*., 152, 57-101.

Ochsner T.E., Horton R., Ren T. 2001. A new perspective on soil thermal properties. *Soil Sci. Soc. Am. J*., 65: 1641-1647.

Philip J.R. (1964): Similarity hypothesis for capillary hysteresis in porous materials. *J. Geophys. Res*., 69 , 8: 1553–1562.

Poulovassilis A., Childs E.C. 1971. The hysteresis of pore water: The non-independence of domains. *Soil Sci.*, 112, 301–312.

Shiozawa S., Campbell G.S. 1990. Soil thermal conductivity. *Remote Sensing Rev*., 5: 301-310.

Singh D.N., Devid K. 2000. Generalized relationships for estimating soil thermal resistivity. *Experimental Thermal Fluid Sci*., 22: 133-143.

Thakur V.K.S., Sreedeep S., Singh D.N. 2005. Parameters affecting soil–water characteristic curves of fine-grained soils. *J. Geotechnical and Geoenvironmental Engineering*, 131, 4: 521-524.

Vandervaere J.P., Peugeot C., Vauclin M., Angulo Jaramillo R., Lebel T. 1997. Estimating hydraulic conductivity of crusted soils using disc infiltrometers and minitensiometers. *J. Hydrol*., 189: 203-223.

Van Genuchten M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44: 892-898.

Van Rooyen M., Winterkorn H.F. 1957. Theoretical and practical aspects of the thermal conductivity of soils and similar granular systems. US *Highway Research Board*, Bulletin 159: 58-135.

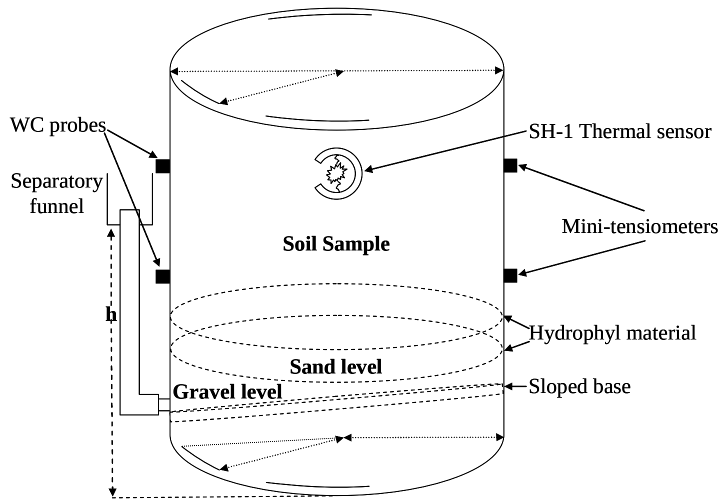

Figure 1. Soil column device scheme used to determine the soil thermal and hydrodynamic properties. WC = FDRs probes to measure water content, h = distance (cm) of the height of displacement of the separatory funnel, SH-1 = thermal sensor to measure thermal properties.

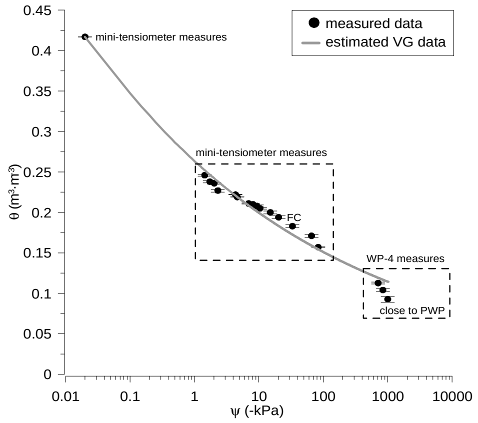

Figure 2. Estimate soil water characteristic curve for the studied silt loam soil, observed values and ± standard error. FC = field capacity, PWP = permanent wilting point.

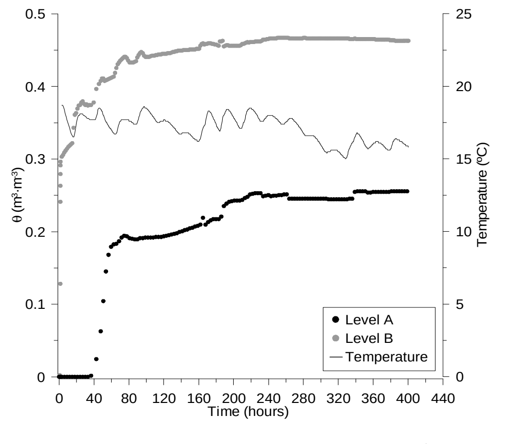

Figure 3. Soil wetting process and temperature daily cycle for the studied soil.

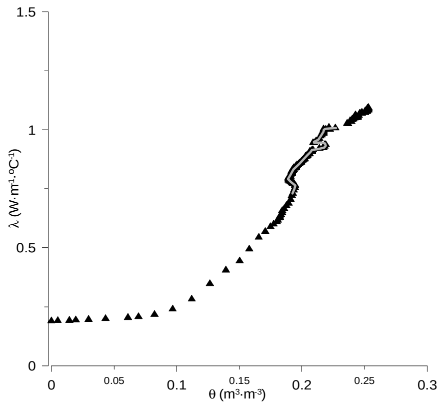

Figure 4. Relation between soil thermal conductivity (λ) and volumetric water content for wetting cycle. Grey line indicates time steps where the soil moisture showed a slight decreasing.

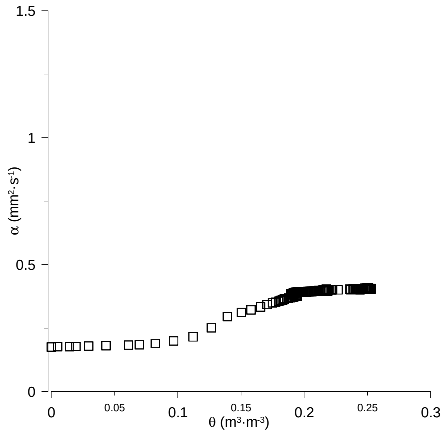

Figure 5. Relation between soil thermal diffusivity (α) and volumetric water content for wetting cycle.

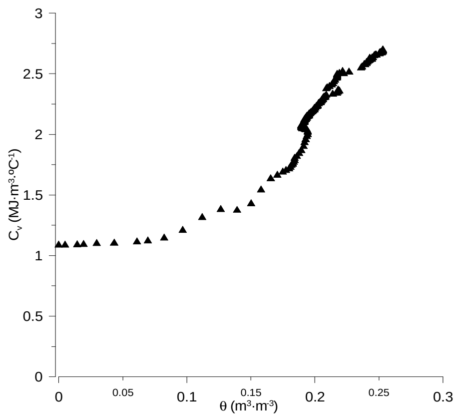

Figure 6. Relation between soil volumetric heat capacity (C_v) and volumetric water content for wetting cycle.

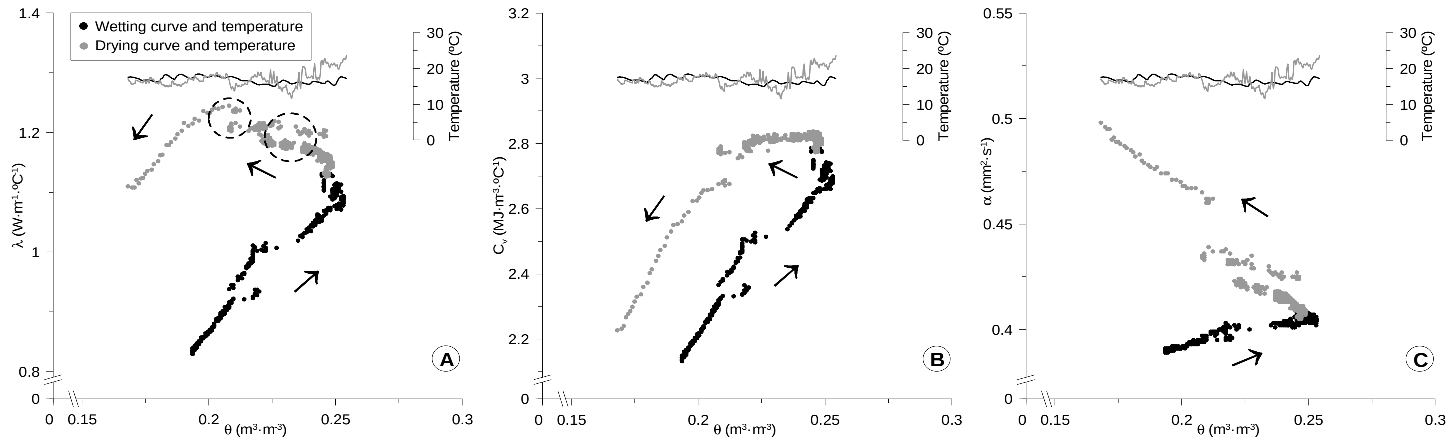

Figure. 7: Wetting and drying curves of the relationship between A: thermal conductivity, B: volumetric heat capacity, C: thermal diffusivity and volumetric water content. The lines are the temperature curves oscillation during both cycles (black corresponds to wet, grey corresponds to dry), the arrows show the direction of the process. In Fig. 7a the dot circles indicate the temperature oscillation during the wetting process.