Thermal diffusivity of Lammellic Arenosols as related to soil moisture

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Abstract. This study presents the thermal diffusivity vs. moisture content curves for sandy soils of the East European Plain. Nine undisturbed soil cores 70 mm in height and 50 mm in diameter were studied in laboratory using the unsteady-state method. Thermal diffusivity of air-dry samples varied from 2.30×10^{-7} to 4.16×10^{-7} m^2 s^{-1}. The experimental moisture content – thermal diffusivity dependencies demonstrated pronounced peaks at 0.03–0.10 m^2 m^{-3} moisture contents. Peak values of thermal diffusivity were from 8.25×10^{-7} to 9.86×10^{-7} m^2 s^{-1}. Statistical analysis was performed for 23 sandy samples including the newly studied ones and those earlier investigated with the same unsteady-state method. The ranges of sand, silt, and clay within the whole dataset were 73–97, 0–25, and 1–6%; wet bulk density varied from 1270 to 1820 kg m^{-3}, organic carbon ranged from 0.1 to 1.7%. Each experimental curve was parameterized with a 4-parameter function. The parameters of average moisture content – thermal diffusivity dependencies were also obtained for (1) all sandy soils, (2) sandy soils with organic carbon content of 0.5% and greater, (3) sandy soils with organic carbon content less than 0.5%.

1. Introduction

Sandy soils are widely spread in many regions of the world, especially in the Central African plateau, Sahelian region of Africa, various parts of the Sahara, central and western Australia, the Near East and western China. All in all, these soils occupy about 1.300 million ha or 10% of land surface [1]. Sandy soils typically demonstrate high heating rates in summer and high cooling rates in winter which results in rather wide ranges of annual temperature dynamics within the soil profile and consequently in high variability of organic matter mineralization rates.

The low thermal inertia of sandy soils is explained by relatively high values of soil thermal diffusivity reported in many studies [2-6]. For example, the highest thermal diffusivities of sand reaching more than 1.2×10^{-8} m^2 s^{-1} were reported in [3]. Thermal properties of sandy soils are highly dependent on soil moisture [2, 4], and so it is a common practice to measure the thermal diffusivity of sands across a range of water contents [6].

Our dataset of previously investigated sandy soils included 14 samples, and this was not enough to provide the reliable statistics. Hence, the main aim of this study was to enlarge the existing dataset of the moisture content – thermal diffusivity dependencies for sandy soils and to provide the possibility to obtain statistically significant parameters of the moisture content – thermal diffusivity curves. To achieve this goal, we studied thermal diffusivities, texture, bulk densities and organic carbon contents for 9 more samples of sandy soils.
2. Objects and methods

Research objects were Lammelic Arenosols sampled in the southeastern part of the Voronezh Region in the Bobrovsky district (51°10’N, 40°18’E) at three plots. Plots 1 and 2 were located on the slopes of a sand dune and the plot 3 was located at the top of the dune. The soil profiles at plots 1, 2, and 3 included buried layers with relatively high organic carbon content.

Undisturbed soil cores were sampled from the 0–1.75 m layer with thin-walled steel cylinders 70 mm in height and 50 mm in diameter. Additional sampling was carried out to provide soil material necessary to investigate soil texture and organic carbon content.

Statistical analysis was performed for the dataset of 23 samples including the newly studied Lammelic Arenosols from Voronezh region and earlier investigated Anthrosols, Brunic Arenosols, and Albic Retisols from Moscow region [5]. Sampling sites are marked in figure 1.

![Figure 1. Location of the sampling sites. Map data ©2019 Google.](image)

Thermal diffusivity was measured in the laboratory using the unsteady-state method [4, 7, 8]. Thermal diffusivity at certain moisture content was determined from the heating curve of sample packed in the waterproof measuring cell and placed into a water bath with a constant temperature of 25°C which was higher than the initial temperature of the sample (about 20°C). The heating rate was considered to be proportional to the soil thermal diffusivity. At the beginning of our experiments the studied samples were capillary-moistened with water; the initial volume water contents in the samples varied from 17 to 23%. Then the samples were dried step-by-step and their thermal diffusivity was measured at different water contents until the air-dry state was reached.

After the measurements of soil thermal diffusivity were complete, the samples were dried and soil wet bulk density was determined. The soil texture and percentage of the organic carbon were determined using the pipette method with sodium pyrophosphate pretreatment [9] and the dry combustion method [10].

3. Results

All studied Lammelic Arenosols were sands according to USDA textural classification [11]. Sand, silt, and clay percentages were 89–97, 0–6, and 2–6 (table 1). Organic carbon content varied from 0.1 to 0.9% and didn’t demonstrate any correlation with depth in the layered soil profile. Bulk density was rather high: from 1510 to 1660 kg m$^{-3}$, which is typical for sandy soils.

Thermal diffusivity of air-dry samples varied from 2.30×10$^{-7}$ to 4.16×10$^{-7}$ m$^2$s$^{-1}$. Thermal diffusivity vs. moisture content dependencies had a pronounced maximum within the range of water contents of 0.03–0.10 m$^3$ m$^{-3}$. The high growth rates of thermal diffusivity with water contents in the range of 0.00–0.05 m$^3$ m$^{-3}$ are typical for sandy soils and can be explained as follows. Due to weak interactions with the surface of quartz particles, soil moisture in sandy soils is mobile even at very low water contents, and so the addition of water results in rapid growth of convective heat transfer and the
apparent thermal diffusivity. At high water contents, the radial moisture transport is limited by cylinder walls, and so under the experimental design used, the apparent thermal diffusivity becomes smaller when water content grows.

Thermal diffusivity of moist samples grew twofold to fourfold as compared to the dry samples. Peak values of thermal diffusivity were from $8.25 \times 10^{-7}$ to $9.86 \times 10^{-7}$ m$^2$s$^{-1}$. The lowest values of thermal diffusivity were obtained for samples 5, 6, and 8 with the highest percentages of organic carbon (table 1 and figure 2).

### Table 1. Properties of studied horizons of Lammelic Arenosols.

| Sample ID | Horizon | Depth (m) | Sand (%) | Silt (%) | Clay (%) | Organic carbon (%) | Bulk density (kg m$^{-3}$) | Particle density (kg m$^{-3}$) |
|-----------|---------|-----------|----------|----------|----------|-------------------|---------------------------|-------------------------------|
| 1         | C       | 0.18–0.25 | 97       | 1        | 2        | 0.12              | 1570                      | 2660                          |
| 2         | [AY]    | 0.38–0.45 | 92       | 4        | 4        | 0.33              | 1660                      | 2640                          |
| 3         | [C]     | 0.71–0.78 | 92       | 3        | 5        | 0.10              | 1620                      | 2650                          |
| 4         | [C]     | 1.10–1.17 | 92       | 4        | 4        | 0.07              | 1590                      | 2660                          |
| 5         | AY      | 0.12–0.19 | 90       | 6        | 4        | 0.77              | 1620                      | 2620                          |
| 6         | [C]     | 0.56–0.63 | 89       | 5        | 6        | 0.50              | 1530                      | 2630                          |
| 7         | C       | 0.51–0.58 | 97       | 0        | 3        | 0.09              | 1590                      | 2650                          |
| 8         | [AY]    | 0.76–0.83 | 92       | 3        | 5        | 0.93              | 1510                      | 2630                          |
| 9         | [C]     | 1.66–1.73 | 95       | 2        | 3        | 0.09              | 1560                      | 2650                          |

To compare different $\kappa(\theta)$ curves, where $\kappa$ is thermal diffusivity and $\theta$ is water content, we used a four-parameter approximation [12]:

$$\kappa = \kappa_0 + a \exp \left[ -0.5 \left( \frac{\ln \left( \frac{\theta}{\theta_0} \right)}{b} \right)^2 \right].$$

The suggested approximation has an advantage of clear physical interpretation: $\kappa_0$ is the thermal diffusivity of dry soil, $a$ is the difference between the highest thermal diffusivity at the optional water content $\theta_0$ and the thermal diffusivity of dry soil, $b$ is the half-width of the peak of the $\kappa(\theta)$ curve.

We obtained the parameters of average $\kappa(\theta)$ curves for sandy soils by approximating all the data points for the whole dataset with function (1). We also applied grouping approach which gave good results in soil hydrology [13, 14]. The core idea of this method is grouping soils by texture or by any other basic soil property and then to train the regression models separately on each of the obtained subsets. We noticed that the obtained thermal diffusivities were rather sensitive to organic carbon content, so we decided to divide our dataset into the subsets with different ranges of organic carbon contents, i.e. soils with organic carbon content greater or equal to 0.5% and those with organic carbon content less than 0.5%. The parameters of function (1) for the whole dataset and for two soil groups with different ranges of carbon contents are listed in table 2.
Figure 2. Thermal diffusivity vs. water content dependencies for studied horizons of Lammelic Arenosols: experimental data (symbols) and approximating curves.

The quality of obtained approximating functions was evaluated using three model performance metrics: (1) the less informative but widely used Pearson’s correlation coefficient between the model-predicted and observed values $R^2$, (2) the root mean square error (RMSE) which is also widely used but doesn’t allow comparing variables of different ranges, and (3) recently suggested dimensionless refined Willmott index of agreement between the model-predicted and observed values $d_r$ which approaches 1.0 when the predictions approach the observations [15].

Table 2. Parameters of average $\kappa(\theta)$ curves for the whole dataset and for the subsets with different ranges of organic carbon contents ($C$).

| Dataset    | $\kappa_0$, m$^2$s$^{-1}$ | $\alpha$, m$^2$s$^{-1}$ | $\theta_i$, m$^3$ | $b$    | $R^2$    | RMSE, m$^2$s$^{-1}$ | $d_r$   |
|------------|-----------------|-----------------|-----------------|-------|---------|---------------------|-------|
| All sands  | $2.981\times10^{-7}$ | $5.732\times10^{-7}$ | 0.104           | 1.182 | 0.849   | $6.571\times10^{-8}$ | 0.796 |
| $C \geq 0.5\%$ | $3.031\times10^{-7}$ | $5.247\times10^{-7}$ | 0.119           | 1.056 | 0.943   | $3.660\times10^{-8}$ | 0.877 |
| $C < 0.5\%$ | $2.974\times10^{-7}$ | $6.039\times10^{-7}$ | 0.098           | 1.209 | 0.875   | $6.173\times10^{-8}$ | 0.819 |

All model performance metrics confirmed the efficiency of grouping soils: the average curves for two groups differing in organic carbon ranges turned out to be more precise than the average curve obtained for the whole dataset. Grouping soils by organic carbon resulted in lessening of RMSE and in growth of both $R^2$ and $d_r$ (table 2). Hence in the case when the information on organic carbon content is available, we recommend using the parameters of function (1) for the corresponding organic carbon range. When there is no information on organic carbon, one can use the parameters listed in the first...
row of table 2. In this case the model performance metrics will slightly worsen, nevertheless remaining at rather high levels of 0.85 for R² and almost 0.8 for index of agreement.

4. Conclusions
Thermal diffusivity of studied Lammellic Arenosols was rather high and reached up to 10⁻⁶ m² s⁻¹. The water content – thermal diffusivity dependencies had peaks at low water content which is typical for sandy soils. The lowest values of soil thermal diffusivity were obtained for horizons with the highest carbon contents.

Regression formulae were obtained allowing estimating apparent thermal diffusivity of sandy soils from available data on organic carbon and soil water contents or, if there are no data on organic carbon, solely from data on water content.

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