

## Parameters of the Thermal Diffusivity vs. Water Content Function for Mineral Soils of Different Textural Classes

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**Abstract**—This work provides parameters of the soil thermal diffusivity vs. water content function for eight textural classes. The experimental thermal diffusivity vs. water content curves previously obtained for mineral soils of the European Russia were used. In the course of the study, the dataset for 77 undisturbed soil samples was analyzed. This dataset included loose sand, dense sand, sandy loam, light loam, medium loam, heavy loam, light clay, and medium clay. Thermal diffusivity of soil samples measured using the unsteady-state method varied within the dataset from  $0.77 \times 10^{-7}$  to  $10.09 \times 10^{-7}$  m<sup>2</sup>/s. To parameterize the soil thermal diffusivity vs. water content dependences the grouping method was applied. Soils were grouped according to textural classes using the classification either after Dolgov or after Kachinskii. For each of the chosen textural classes, the parameters of an average thermal diffusivity vs. water content curve were estimated from all the experimental data points for this class by approximating these points with the previously suggested four-parameter function. The approximation accuracy was estimated using Willmott's index of agreement between the model-predicted curve and the observed values. The greatest value for the index of agreement (0.845) was obtained for the medium clays defined according to Dolgov and the smallest one (0.532) for sandy loams. The index of agreement for the whole dataset was 0.699 when the textural classes were defined according to Dolgov, and 0.688 when they were defined according to Kachinskii. In addition, the parameters of an average general curve for the whole experimental dataset were obtained. The index of agreement between this general curve and observed values was only 0.554, which confirms the efficiency of soil grouping by textural classes.

**Keywords:** mathematical modeling, grouping method, sands, loams, clays

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### INTRODUCTION

Soil thermal diffusivity is equal to the ratio of soil thermal conductivity to the volumetric thermal capacity, and it varies with the variation of these two parameters. With the increasing thermal conductivity (i.e., the soil ability to transfer heat), the thermal diffusivity also increases; and the temperature of deep soil layers becomes more sensitive to the surface temperature changes. On the contrary, an increase in the thermal capacity (i.e., quantity of heat required to raise the soil temperature) leads to a decrease in thermal diffusivity and, hence, mitigates the temperature response deep in the soil profile to the changing external conditions. Thus, thermal diffusivity, standing for the temperature sensitivity of soil, may change as a result of changes either in soil ability to transfer heat (thermal conductivity), or in its thermal inertia (thermal capacity). Both thermal conductivity and thermal capacity of soils vary significantly with soil moisture content; therefore, the thermal diffusivity of soils also depends substantially on their moisture content [4, 7, 8, 10, 15, 22, 23, 33, 35]. The range of thermal diffusivity variation with moisture and the type of curve  $\kappa(\theta)$  for a specific soil, where  $\kappa$  is thermal diffusivity, and  $\theta$  is the

volumetric moisture content are controlled, above all, by the soil texture, bulk density, and the organic matter content [9, 10, 22, 23].

The rate of soil heating and cooling at different soil moisture contents is controlled by soil thermal diffusivity; therefore, it was suggested that the  $\kappa(\theta)$  dependence should be considered the main soil thermal characteristic [4]. The detailed study of the  $\kappa(\theta)$  curve allows estimating the sensitivity of thermal diffusivity to soil moisture fluctuations, which may be useful for obtaining the long-term forecasts of soil temperature, as well as for analysis of problems related to soilscape genesis and functioning [5, 6].

Many present-day publications concerning thermal properties are focused mainly on the thermal conductivity [24, 26, 34, 38, 39, 41]. In climatic and hydrological models, the data on experimentally obtained or estimated soil thermal conductivity are supplemented by the calculated values of volumetric thermal capacity obtained using the additive de Vries model [27, 30, 37, 42]. De Vries model [27] was trained built on a small dataset, and many authors were skeptical about the numerical values of de Vries model parameters, i.e., thermal capacity of soil

organic matter and that of water in the soil pores [1, 11, 12, 18]. So, it seems that to predict soil temperature regime, the use of only one (either measured directly or estimated) thermal parameter, namely, the thermal diffusivity, should result in more accurate forecasts than the use of two thermal parameters, i.e., thermal conductivity and thermal capacity, each of which being estimated with a certain error. At present, many authors study and simulate thermal diffusivity of soils [3, 4, 19, 20, 22, 25, 28, 29, 35, 40, 44]. In most cases, these investigations are performed for a small number of samples and may be qualified as regional ones.

When modeling soil thermal diffusivity, the empirical approach is usually applied basing on the experimental dependencies between thermal diffusivity and soil moisture content approximated by a certain function. Next, regression equations are obtained using statistical methods; these equations allow estimating the approximation function parameters from the data on basic soil properties of soils, primarily, from texture and bulk density and/or the organic matter content [3, 20, 23, 44]. Similar procedures are applied when modeling the hydraulic soil properties [36].

In soil hydrology, good results were obtained when mathematical models were based on grouping soils [32]. When applying this method, the model is split horizontally, i.e., different regression equations are obtained to calculate the model parameters for soils of different textures [31]. Textural grouping is also used when modeling soil thermal diffusivity [16, 23, 44]. The second approach, widely used in hydrology now, involves the vertical hierarchy of models, i.e., depending on the available data on basic soil properties, the model is chosen that can work with these data without any supplementary information. This approach allows obtaining model estimates even from the minimal amount of input data. For example, ROSETTA computer program allows calculating the water-retention curve parameters from data on soil texture and bulk density, but it is also able to provide a tentative estimate of water-retention curve parameters using only the textural class name according to the USDA soil texture classification [36]. It turned out that using the ROSETTA software with the input data on sand, silt, and clay percentages, almost did not increase the model accuracy as compared to the case when the only input information were textural class names, and the average water-retention curves for the given soil classes were used [36].

This paper presents the algorithms for estimating thermal diffusivity at different moisture contents based on the experimental data for 77 soil samples with textures ranging from loose sand to medium clay. These algorithms represent the model of the first hierarchical level, since only the textural class names are used as input data. The output data are tabulated parameters of the function describing the dependence of soil thermal diffusivity on moisture content different for different textural classes.

Two approaches to splitting the available experimental data according to textural classes were used and compared. In the modern guidebook "Theories and methods in the soil physics" [21], two approaches are mentioned: these are the approaches of Kachinskii [14] and Dolgov [13]. Both identify the textural position of soil by the content of physical clay, i.e., the particles less than  $1 \times 10^{-5}$  m in size. The use of the Kachinskii's classification implies different boundaries between textural classes for the soils of different soil-formation types [14]. For example, the soil with 55% physical clay is classified by Kachinskii as a light clay in case it is of podzolic pedogenesis, and it is classified as a heavy loam, in case it is the soil of steppe pedogenesis with a high potential aggregation ability. Voronin noted [8] that not everybody agreed to take the soil formation type into account when defining the soil textural class. In the methodical guidebook edited by Dolgov [13], it was emphasized that the soil classification by texture should be based exclusively on the content of particles of different sizes in soil; therefore, Dolgov proposes a universal classification for all soil types. It implies the same grades of physical clay content (in particular, those that are used for podzolic soils in Kachinskii's classification) for determining the soil textural classes regardless of the type of soil formation.

In general, when developing mathematical models, it appears more appropriate to use a formal quantitative approach excluding any qualitative indices that depend on the expert opinion. In addition, among different models of similar accuracy, the preference is given to those requiring less input data. Therefore, the Dolgov's approach to soil textural classification based on the physical clay content only, appears to be preferable, at the first glance, as compared to the Kachinskii's approach. However, for the substantiated choice between the Dolgov's and Kachinskii's classifications in the context of the problem discussed, we should compare the accuracy of soil thermal diffusivity estimates for using two variants of soil grouping by texture i.e., with and without taking into account the type of pedogenesis.

In the course of the study, the available data were grouped by texture using two above-mentioned approaches to compare the modeling results and to choose the variant of soil grouping by texture that allows uniting soils with close thermal diffusivities into different groups more adequately. The work was aimed at obtaining a set of equations for estimating soil thermal diffusivity at different moisture basing on the textural class names.

## OBJECTS AND METHODS

The model curves were developed using the experimental dependences between the thermal diffusivity and moisture content earlier obtained for sandy, loamy and clayey soils in the European part of Russia [4, 7, 15, 17]. The objects of study included the soddy-podzolic weakly differentiated sandy loamy and sandy arable soils (Brunic Arenosols and Arenosols (Aric)) (Chash-

nikovo test plot, Moscow oblast, 56°2' N, 37°10' E), soddy weakly podzolic sandy soils (Albic Retisols) (Prioksko-Terrasnyi biosphere reserve, Moscow oblast, 54°55' N, 37°34' E), loamy gray forest soils and soils with the second humus horizon (Albic Luvisols (Siltic)) (Vladimirske opol'e, 56°23' N, 40°25'E), light gray forest cultivated medium loamy soil (Albic Luvisol (Aric) (Zaokskie pitomniki, Tula oblast, 54°36' N, 37°26' E), ordinary chernozem medium-thick light-clayey (Haplic Chernozem (Clayic, Pachic) (Kamen-naya steppe, Voronezh oblast, 51°03' N, 40°43' E), meadow-chernozemic leached medium loamy arable soil (Epigleyic Chernic Phaeozem (Aric)) (Ignat'evskii settlement, Adygeya Republic, 44°50' N, 40°30' E).

Soil cores with undisturbed structure were sampled with metal thin-walled cylinders. Samples from the Kammennaya steppe plot were 0.07 and 0.05 m in height and diameter; all the rest, 0.10 and 0.038 m, respectively.

Thermal diffusivity of samples was measured in the laboratory using the unsteady-state method [4, 22, 33]. For each sample, a series of measurements was performed in the regime of sample heating from 20 to 25°C to obtain the dependence of apparent thermal diffusivity vs. moisture content in the range from capillary saturated to air-dry samples.

The statistical analysis was carried out for 77 samples using 836 experimental values of soil thermal diffusivity at different moisture contents. Bulk density of samples from the dataset varied from 860 to 1820 kg/m<sup>3</sup>; the organic carbon content, from 0.1 to 6.5%; the content of physical clay, from 1 to 76%; and thermal diffusivity, from  $0.77 \times 10^{-7}$  to  $10.09 \times 10^{-7}$  m<sup>2</sup>/s (Table 1).

In the majority of cases, the thermal diffusivity of the studied soils increased with the increasing moisture to reach the constant level; in some cases at high moisture contents, thermal diffusivity decreased somewhat to show the maximum at the experimental curve. Minimums of thermal diffusivity were observed at low moisture contents, within 0.00–0.15 m<sup>3</sup>/m<sup>3</sup>; and maximums, at the moisture content ranging from 0.08 to 0.54 m<sup>3</sup>/m<sup>3</sup>. As a whole, thermal diffusivity changed by 1.7–3.7 times with changing moisture contents, and only in two cases the ratio of maximal to minimal values of thermal diffusivities was 4.4 and 5.0. For certain samples, the minimal thermal diffusivities varied within  $(0.77\text{--}4.21) \times 10^{-7}$  m<sup>2</sup>/s; and the maximal thermal diffusivities ranged within  $(2.27\text{--}10.09) \times 10^{-7}$  m<sup>2</sup>/s.

Splitting by textural classes was performed in two variants using the classifications by Dolgov [13] and Kachinskii [14]. According to the Dolgov's classification, we identified 6 loose sands, 8 dense sands, 4 sandy loams, 2 light loams, 11 medium loams, 27 heavy loams, 6 light clays and 13 medium clays. When using the Kachinskii's classification, some heavy loams and clays of the steppe pedogenesis moved to lighter classes. As a result, the number of sands, sandy loams and light loams remained the same

as in the Dolgov's classification, the number of medium loams grew up to 21, the number of heavy loams decreased to 18, that of light clays increased to 17, and the only one medium clay sample remained.

For each textural class, the parameters of average dependence between thermal diffusivity and moisture content were estimated using all experimental datapoints related to the given class. These datapoints were approximated by the earlier suggested four-parameter function [2, 3]:

$$\kappa = \kappa_0 + a \exp \left[ -0.5 \left( \frac{\ln \left( \frac{\theta}{\theta_0} \right)}{b} \right)^2 \right]. \quad (1)$$

For curves with the maximum, the parameters of function (1) can be interpreted quite clearly:  $\kappa_0$  is the minimal thermal diffusivity of soil;  $\theta_0$  is the moisture content, upon which the maximal thermal diffusivity is reached;  $\kappa_0 + a$  is the maximal thermal diffusivity at moisture content  $\theta_0$ . Parameter  $b$  shows the peak width; the lower is  $b$ , the better S-shape of curve is pronounced. Function (1) may be also used for parameterization of S-shaped experimental dependences without any peaks, even almost linear ones. For quasilinear and S-shaped curves, parameter  $\kappa_0$  interpretation is the same: it stands for the minimal thermal diffusivity of soil. Parameter  $a$  is the measure of thermal diffusivity growth with the changing moisture content; parameter  $b$  characterizes the width of moisture range, where the main growth of thermal diffusivity takes place. For curves without a peak, parameter  $\theta_0$  may be interpreted as a coordinate of the virtual maximum, which moves rightwards along the moisture axis as the  $\kappa(\theta)$  dependence becomes less S-shaped and approaches a linear shape.

In addition to  $\kappa_0$ ,  $a$ ,  $\theta_0$ , and  $b$  parameters for each textural class, the parameters of general average curve  $\kappa(\theta)$ , developed on the basis of all available data were also obtained.

The accuracy of experimental data approximation by function (1) was estimated by the dimensionless Willmott's index of agreement  $d_t$  [43]:

$$d_t = \begin{cases} 1 - \frac{\sum_{i=1}^n |P_i - O_i|}{2 \sum_{i=1}^n |O_i - \bar{O}|}, & \text{when } \sum_{i=1}^n |P_i - O_i| \leq 2 \sum_{i=1}^n |O_i - \bar{O}| \\ \frac{2 \sum_{i=1}^n |O_i - \bar{O}|}{\sum_{i=1}^n |P_i - O_i|} - 1, & \text{when } \sum_{i=1}^n |P_i - O_i| > 2 \sum_{i=1}^n |O_i - \bar{O}| \end{cases}, \quad (2)$$

where  $P_i$  are model predictions,  $O_i$  are the pairwise-matched observations,  $n$  is the number of  $P_i - O_i$  pairs,  $\bar{O}$  is the observed mean. When the predictions approach the observations,  $d_t$  approaches 1.

**Table 1.** Physical clay (PC) percentage, ranges of moisture ( $\theta$ ) and thermal diffusivity ( $\kappa$ ) in the analyzed samples

No.	Soil code*	Soil textural name**	Horizon	Depth, m	PC, %	$\theta$ , m <sup>3</sup> /m <sup>3</sup>	$\kappa$ , m <sup>2</sup> /s	Source
1	A	Medium loam	Ap	0.05–0.15	33	0.02–0.37	$(2.33–4.21) \times 10^{-7}$	[15]
2	A	Medium loam	Ap	0.05–0.15	35	0.01–0.38	$(2.30–4.28) \times 10^{-7}$	[15]
3	A	Medium loam	Ap	0.05–0.15	35	0.01–0.40	$(2.29–4.40) \times 10^{-7}$	[15]
4	A	Heavy loam (Medium loam)	A1B	0.45–0.55	43	0.02–0.34	$(2.44–4.37) \times 10^{-7}$	[15]
5	A	Heavy loam	A1B	0.45–0.55	45	0.02–0.35	$(2.60–4.62) \times 10^{-7}$	[15]
6	A	Heavy loam	A1B	0.45–0.55	48	0.02–0.33	$(2.38–4.37) \times 10^{-7}$	[15]
7	B	Dense sand	Ap	0.05–0.15	9	0.01–0.32	$(2.40–5.91) \times 10^{-7}$	[15]
8	B	Dense sand	Ap	0.05–0.15	7	0.01–0.32	$(2.61–5.60) \times 10^{-7}$	[15]
9	B	Dense sand	Ap	0.05–0.15	8	0.01–0.29	$(2.10–5.09) \times 10^{-7}$	[15]
10	B	Loose sand	A2B	0.45–0.55	3	0.01–0.26	$(2.83–7.42) \times 10^{-7}$	[15]
11	B	Loose sand	A2B	0.45–0.55	2	0.01–0.26	$(1.94–6.52) \times 10^{-7}$	[15]
12	B	Loose sand	A2B	0.45–0.55	2	0.01–0.23	$(2.28–5.44) \times 10^{-7}$	[15]
13	B	Sandy loam	Ap	0.05–0.15	21	0.02–0.36	$(2.39–5.12) \times 10^{-7}$	[15]
14	B	Sandy loam	Ap	0.05–0.15	20	0.02–0.38	$(2.13–4.49) \times 10^{-7}$	[15]
15	B	Sandy loam	Ap	0.05–0.15	20	0.02–0.36	$(2.30–5.24) \times 10^{-7}$	[15]
16	B	Dense sand	A2B	0.45–0.55	8	0.01–0.27	$(4.21–9.09) \times 10^{-7}$	[15]
17	B	Dense sand	A2B	0.45–0.55	9	0.01–0.26	$(4.14–9.06) \times 10^{-7}$	[15]
18	B	Dense sand	A2B	0.45–0.55	9	0.01–0.27	$(4.02–9.20) \times 10^{-7}$	[15]
19	C	Heavy loam (Medium loam)	Ap	0.05–0.15	40	0.05–0.35	$(1.44–3.69) \times 10^{-7}$	[17]
20	C	Light clay (Heavy loam)	Ap	0.05–0.15	50	0.06–0.38	$(1.20–3.08) \times 10^{-7}$	[17]
21	C	Heavy loam (Medium loam)	Ap	0.05–0.15	42	0.07–0.37	$(1.45–4.11) \times 10^{-7}$	[17]
22	C	Heavy loam (Medium loam)	A1	0.30–0.40	42	0.06–0.45	$(1.21–3.53) \times 10^{-7}$	[17]
23	C	Heavy loam (Medium loam)	A1	0.30–0.40	43	0.05–0.43	$(1.34–3.70) \times 10^{-7}$	[17]
24	C	Medium loam	A1	0.30–0.40	39	0.06–0.43	$(1.35–3.85) \times 10^{-7}$	[17]
25	C	Medium loam	A1B	0.46–0.56	39	0.04–0.36	$(1.35–2.96) \times 10^{-7}$	[17]
26	C	Medium loam	A1B	0.46–0.56	39	0.05–0.38	$(1.51–3.73) \times 10^{-7}$	[17]
27	C	Heavy loam (Medium loam)	A1B	0.46–0.56	40	0.05–0.37	$(1.57–3.54) \times 10^{-7}$	[17]
28	D	Dense sand	Ap	0.05–0.15	5	0.00–0.38	$(2.42–7.79) \times 10^{-7}$	[15]
29	D	Loose sand	BC	0.25–0.35	3	0.00–0.30	$(3.00–9.93) \times 10^{-7}$	[15]
30	D	Sandy loam	C1	0.70–0.80	19	0.01–0.21	$(4.11–9.69) \times 10^{-7}$	[15]
31	D	Light loam	C2g	0.90–1.00	29	0.04–0.33	$(2.04–5.28) \times 10^{-7}$	[15]
32	D	Dense sand	AE	0.04–0.14	8	0.00–0.34	$(2.45–7.58) \times 10^{-7}$	[15]
33	D	Loose sand	B(BC)	0.25–0.35	3	0.00–0.24	$(2.22–9.84) \times 10^{-7}$	[15]
34	D	Loose sand	C1	0.65–0.75	1	0.01–0.23	$(2.00–10.09) \times 10^{-7}$	[15]
35	D	Light loam	C2	0.90–1.00	26	0.01–0.25	$(3.11–8.14) \times 10^{-7}$	[15]
36	E	Medium clay (Light clay)	Ap	0–0.07	68	0.07–0.45	$(1.44–2.69) \times 10^{-7}$	[7]
37	E	Medium clay (Light clay)	Ap	0–0.07	68	0.07–0.43	$(1.05–2.48) \times 10^{-7}$	[7]

Table 1. (Contd.)

No.	Soil code*	Soil textural name**	Horizon	Depth, m	PC, %	$\theta$ , m <sup>3</sup> /m <sup>3</sup>	$\kappa$ , m <sup>2</sup> /s	Source
38	E	Medium clay (Light clay)	Ap	0.10–0.17	70	0.08–0.38	$(0.77–2.69) \times 10^{-7}$	[7]
39	E	Medium clay (Light clay)	Ap	0.10–0.17	70	0.09–0.44	$(0.77–2.89) \times 10^{-7}$	[7]
40	E	Medium clay (Light clay)	A1	0.30–0.37	73	0.10–0.43	$(0.86–2.58) \times 10^{-7}$	[7]
41	E	Medium clay (Light clay)	AB	0.46–0.53	72	0.06–0.38	$(0.93–2.87) \times 10^{-7}$	[7]
42	E	Medium clay	Bca	0.86–0.93	76	0.07–0.38	$(0.98–3.12) \times 10^{-7}$	[7]
43	E	Medium clay (Light clay)	Asod	0–0.07	68	0.06–0.45	$(1.00–2.60) \times 10^{-7}$	[7]
44	E	Medium clay (Light clay)	Asod	0–0.07	65	0.06–0.47	$(0.82–2.32) \times 10^{-7}$	[7]
45	E	Light clay	A1	0.12–0.19	64	0.06–0.42	$(0.78–2.27) \times 10^{-7}$	[7]
46	E	Medium clay (Light clay)	A1	0.12–0.19	65	0.07–0.40	$(0.90–2.31) \times 10^{-7}$	[7]
47	E	Medium clay (Light clay)	A1	0.40–0.47	70	0.06–0.46	$(0.90–2.56) \times 10^{-7}$	[7]
48	E	Medium clay (Light clay)	B	0.75–0.82	73	0.07–0.40	$(1.01–3.33) \times 10^{-7}$	[7]
49	E	Medium clay (Light clay)	Bca	1.05–1.12	73	0.06–0.37	$(0.98–3.26) \times 10^{-7}$	[7]
50	F	Heavy loam	Ap	0.13–0.23	42	0.04–0.43	$(1.72–4.71) \times 10^{-7}$	[4]
51	F	Light clay	B	0.30–0.40	55	0.05–0.44	$(1.56–4.87) \times 10^{-7}$	[4]
52	J	Heavy loam	Ap	0.14–0.24	43	0.05–0.43	$(2.40–5.02) \times 10^{-7}$	[4]
53	J	Heavy loam	EB	0.30–0.40	41	0.06–0.44	$(2.98–5.90) \times 10^{-7}$	[4]
54	H	Heavy loam	Ap	0.14–0.24	41	0.06–0.46	$(1.80–4.35) \times 10^{-7}$	[4]
55	H	Heavy loam	Ah	0.30–0.40	45	0.05–0.54	$(1.69–3.37) \times 10^{-7}$	[4]
56	H	Heavy loam	EB	0.65–0.75	49	0.06–0.41	$(1.93–4.97) \times 10^{-7}$	[4]
57	I	Heavy loam (Medium loam)	A1	0.10–0.20	40	0.03–0.47	$(1.76–3.80) \times 10^{-7}$	[4]
58	I	Heavy loam	EB	0.30–0.40	43	0.03–0.39	$(2.26–5.27) \times 10^{-7}$	[4]
59	I	Light clay	Bhfg	0.55–0.65	52	0.05–0.41	$(1.06–3.95) \times 10^{-7}$	[4]
60	I	Light clay	Bhfg	0.65–0.75	51	0.06–0.40	$(1.13–4.07) \times 10^{-7}$	[4]
61	H	Heavy loam	Ap	0.05–0.15	41	0.03–0.38	$(1.92–4.89) \times 10^{-7}$	[4]
62	H	Heavy loam	Ah	0.20–0.30	42	0.03–0.47	$(2.10–4.32) \times 10^{-7}$	[4]
63	H	Heavy loam	AE	0.30–0.40	42	0.03–0.46	$(1.90–3.75) \times 10^{-7}$	[4]
64	H	Heavy loam (Medium loam)	EB	0.50–0.60	40	0.04–0.37	$(2.70–5.72) \times 10^{-7}$	[4]
65	H	Medium loam	A1	0.10–0.20	37	0.03–0.46	$(2.10–4.17) \times 10^{-7}$	[4]
66	H	Medium loam	Ap	0.20–0.30	43	0.04–0.38	$(2.56–5.16) \times 10^{-7}$	[4]
67	H	Medium loam	AE	0.33–0.43	38	0.03–0.39	$(2.88–5.23) \times 10^{-7}$	[4]
68	H	Heavy loam	EB	0.48–0.58	47	0.05–0.33	$(2.72–5.37) \times 10^{-7}$	[4]
69	J	Medium loam	Ap	0.20–0.30	37	0.04–0.33	$(2.36–4.90) \times 10^{-7}$	[4]
70	J	Heavy loam	EB	0.32–0.42	42	0.04–0.34	$(2.80–5.68) \times 10^{-7}$	[4]
71	J	Heavy loam	B	0.42–0.52	44	0.05–0.34	$(2.13–5.49) \times 10^{-7}$	[4]

Table 1. (Contd.)

No.	Soil code*	Soil textural name**	Horizon	Depth, m	PC, %	$\theta$ , m <sup>3</sup> /m <sup>3</sup>	$\kappa$ , m <sup>2</sup> /s	Source
72	H	Medium loam	Ap	0.10–0.20	36	0.03–0.43	$(2.19–4.34) \times 10^{-7}$	[4]
73	H	Heavy loam (Medium loam)	Ah	0.30–0.40	40	0.03–0.47	$(2.36–4.00) \times 10^{-7}$	[4]
74	J	Heavy loam (Medium loam)	Ap	0.10–0.20	40	0.04–0.42	$(2.19–4.61) \times 10^{-7}$	[4]
75	J	Heavy loam	EB	0.25–0.35	42	0.03–0.40	$(2.51–4.57) \times 10^{-7}$	[4]
76	J	Light clay	B	0.40–0.50	51	0.05–0.40	$(1.88–4.43) \times 10^{-7}$	[4]
77	J	Medium loam	Ap	0–0.10	39	0.04–0.35	$(2.29–4.92) \times 10^{-7}$	[4]

\* (A) Light gray forest; (B) Soddy-podzolic weakly differentiated; (C) Meadow-chernozemic leached; (D) Soddy-weakly podzolic; (E) Ordinary chernozem medium thick; (F) Gray forest weakly podzolized; (J) Gray forest strongly podzolized; (H) Gray forest with second humus horizon strongly podzolized; (I) Gray forest with gleying features.

\*\* According to Dolgov classification; in case the soil names differ by Kachinskii and Dolgov's classifications, the name after Kachinskii's classification is given in parenthesis.

For both variants of dataset splitting, the Willmott's index was calculated for each textural class as well as for the whole dataset. For each of textural classes, parameters  $\kappa_0$ ,  $a$ ,  $\theta_0$ ,  $b$  were determined using the minimal squares method, and soil thermal diffusivity was estimated for all moisture content values, for which the experimental data on thermal diffusivity were available. Next, for each textural class, the Willmott's index was calculated using the  $P_i-O_i$  pairs for this class. The Willmott index was calculated for the entire dataset using all  $P_i-O_i$  pairs for all textural classes obtained from the above-described algorithm. This procedure was repeated twice: upon splitting the dataset into classes according to the Dolgov's and Kachinskii's classifications.

For the general average curve, developed on the basis of all the data available, the Willmott's index was determined using parameters of this curve. The observed data were compared with the estimated thermal diffusivities using the same parameters of function (1) for all samples.

The indices of agreement for the entire dataset obtained upon its splitting into textural classes after Dolgov and Kachinskii were compared to each other and to the index of agreement for the general average curve developed using all the data available.

## RESULTS AND DISCUSSION

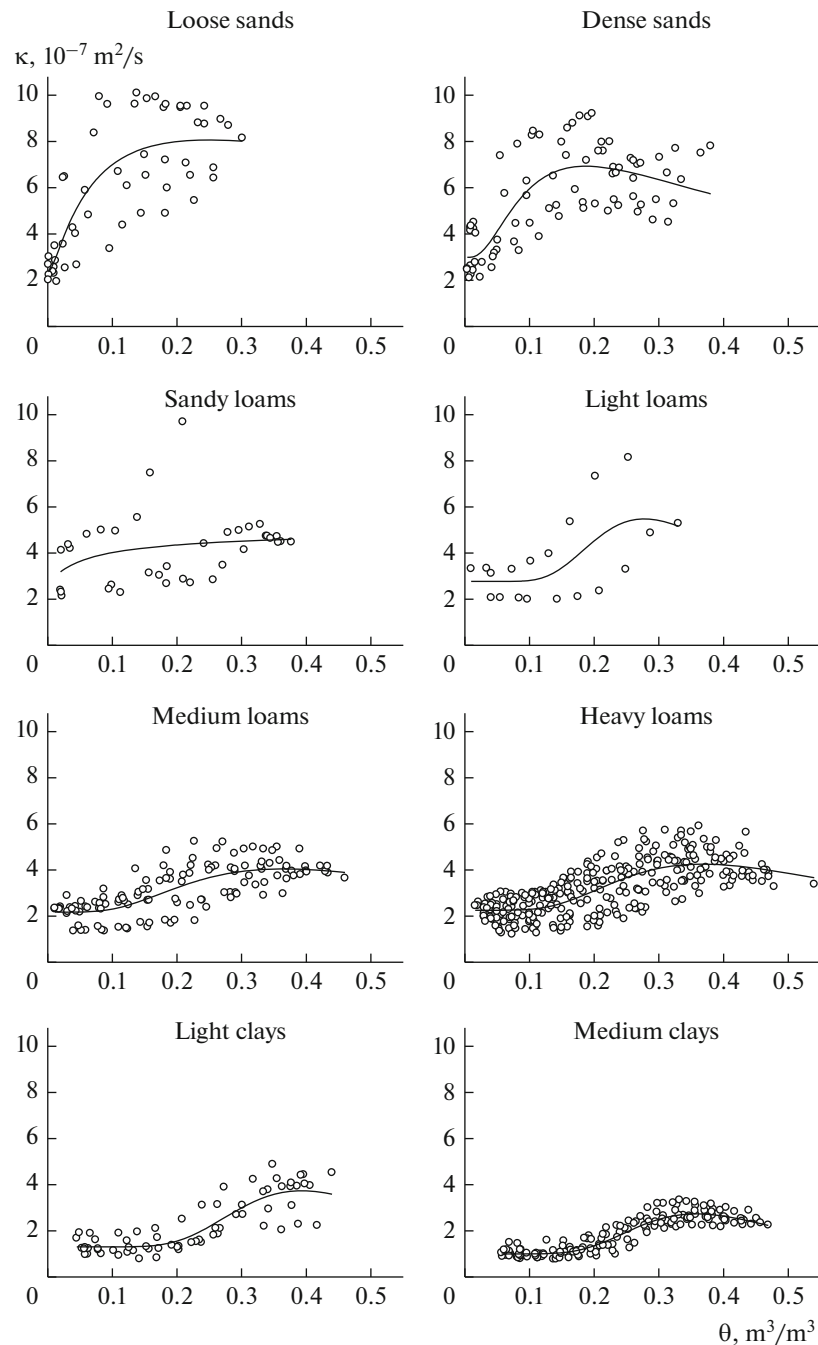
Figures 1 and 2 present the average curves  $\kappa(\theta)$  for different textural classes and for the entire dataset, as well as the experimental data used for developing each of these curves. Dependences between thermal diffusivity and moisture content for soils of different textures differ by the range of thermal diffusivity variation with soil moisture by the absence or presence of a flat segment of the curve at low moisture content, by the markedness of thermal diffusivity maximum, and by scatter of experimental datapoints.

Flat segments of the curve, where soil thermal diffusivity almost does not change with changing moisture content correspond to the moisture content ranges, within which both thermal conductivity and thermal capacity increase similarly with the growing moisture content, so that the ratio of thermal conductivity to thermal capacity (i.e., thermal diffusivity) remains nearly the same. Thermal diffusivity grows with the growing moisture content in case when thermal conductivity grows more quickly than thermal capacity. The opposite is also true: when the growth of thermal conductivity with growing moisture content (e.g., due to pore-plugging water that complicates the convective heat exchange), thermal capacity may increase more quickly than thermal conductivity, thus resulting in a decrease in thermal diffusivity.

Both grouping variants show similar trends. The curves for sandy soils are characterized by a sharp increase in soil thermal diffusivity when wetting in the range of low moisture content (less than 0.1 m<sup>3</sup>/m<sup>3</sup>) with the subsequent slowing down the growth of thermal diffusivity or even its decreasing with the following growth of moisture content (Fig. 1). The absence of a flat segment in the left part of  $\kappa(\theta)$  curve is explained by a low moisture adsorption on the solid particles and by the presence of large pores, which results in moisture remaining mobile and contributing to heat transfer in sandy soils even at low moisture contents.

S-shaped curves typical for loamy and clayey soils include two flat segments in the areas of low and high moisture contents and a relatively gentle transition between them; a weakly pronounced maximum may be observed at moisture contents of 0.3–0.4 m<sup>3</sup>/m<sup>3</sup> (Figs. 1, 2).

The average curve for sandy loams (Fig. 1) was developed using data for only four samples, three of them (13–15) being taken from the Ap horizon with the bulk density of 1430–1470 kg/m<sup>3</sup> and the organic carbon content of 2.2–2.4%; thermal diffusivity of

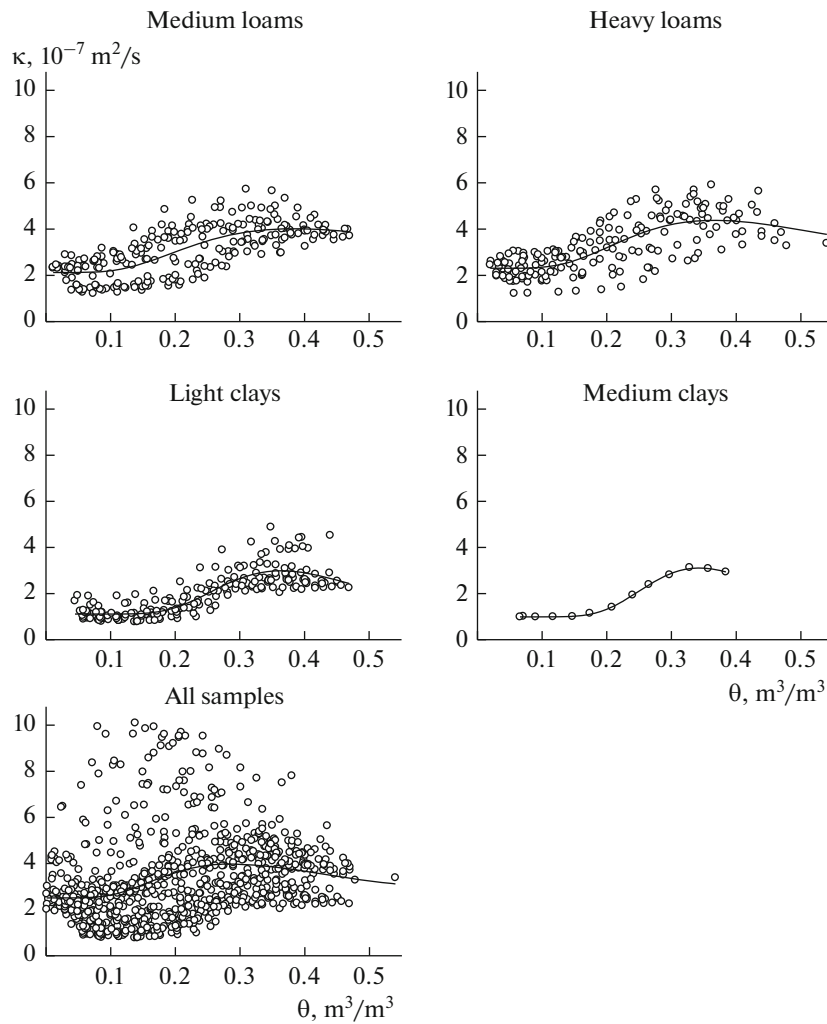


**Fig. 1.** Average  $\kappa(\theta)$  curves and experimental datapoints (symbols) for loose sands, dense sands, sandy loams, light loams, medium loams, heavy loams, light clays, and medium clays according to the Dolgov's classification.

these samples ranged within  $(2.13\text{--}5.24) \times 10^{-7} \text{ m}^2/\text{s}$ . Another sample classified as sandy loam (30) was taken from the C1 horizon at a depth of 0.70–0.80 m; the sample bulk density was equal to  $1760 \text{ kg}/\text{m}^3$ ; and the organic carbon content, to 0.2%. A high bulk density and a low content of organic carbon explain a much higher (as compared to samples from the Ap horizon) thermal diffusivity of sample 30, which varied within  $(4.11\text{--}9.69) \times 10^{-7} \text{ m}^2/\text{s}$ . Thus, the average curve for sandy loams was developed on the basis of a small

number of samples with substantially different bulk densities and organic carbon contents, which resulted in a wide scatter of experimental data and probably does not allow considering the average curve for sandy loams as a representative curve.

The average curve for light loams neither appears to be representative enough (Fig. 1), as it was developed using the data on two samples only (31 and 35), collected at one and the same site in the Prioksko-Terrasnyi Biospheric Reserve from same depth (0.90–



**Fig. 2.** Average  $\kappa(\theta)$  curves and experimental datapoints (symbols) for medium loams, heavy loams, light clays, and medium clay according to the Kachinskii's classification; for all studied samples.

1.00 m) and manifesting the similar bulk density ( $1660 \text{ kg/m}^3$ ) and the organic carbon content (0.2%). Gleying features in sample 31, which are not manifested in sample 35, is the only difference between these samples. Thermal diffusivity of the gleyed soil turned out to be significantly lower (Table 1), which may be explained by the thermo-insulating effect of loose films of amorphous iron. This effect was earlier observed in the gleyed light clayey soil in the depression at the Vladimir Opolie [4].

In general, a considerable scatter of experimental thermal diffusivities is observed almost in each textural class, which may be above all due to the variability of soil bulk densities and the organic carbon contents, and in some cases, due to the presence of amorphous iron. At the same time, the dataset grouping by textural classes revealed the following trend: the soil thermal diffusivity decreases regularly from loose sands ( $1.94\text{--}10.09$ )  $\times 10^{-7} \text{ m}^2/\text{s}$  to medium clays ( $0.77\text{--}$

$3.33$ )  $\times 10^{-7} \text{ m}^2/\text{s}$ . Both the range of thermal diffusivity variability with soil moisture contents and the shape of average curves change in this sequence.

Table 2 lists the parameters of average curves for the textural classes specified after Dolgov and Kachinskii as well as the indices of agreement showing the scatter of experimental datapoints relative to these curves. It is clearly seen that the  $\kappa_0$  parameter fitting the minimal value of thermal diffusivity, generally decreases with the growth of clay percentage, and conductivity and the most abrupt fall of this parameter corresponds to the transition from heavy loams to light clays. Parameter  $a$ , describing the difference between the maximal and the minimal soil thermal diffusivities also decreases as the soil texture becomes heavier; however, in this case, the maximal decrease corresponds to the transition from loose to dense sands and then to sandy loams.

Visually, the scatter of experimental datapoints as related to the average curves for textural classes seems



**Table 2.** Parameters of average dependence between thermal diffusivity and moisture content  $\kappa_0$ ,  $a$ ,  $\theta_0$ ,  $b$  and corresponding values of the Willmott's index of agreement  $d_r$  for certain textural classes and for the general curve developed for all samples

Soil name by texture	Number of samples	$\kappa_0$ , m <sup>2</sup> /s	$a$ , m <sup>2</sup> /s	$\theta_0$ , m <sup>3</sup> /m <sup>3</sup>	$b$	$d_r$
Textural classes after Dolgov and Kachinskii						
Loose sands	6	$2.364 \times 10^{-7}$	$5.697 \times 10^{-7}$	0.249	1.419	0.706
Dense sands	8	$2.986 \times 10^{-7}$	$3.941 \times 10^{-7}$	0.187	0.833	0.673
Sandy loams	4	$2.221 \times 10^{-7}$	$2.550 \times 10^{-7}$	1.135	2.891	0.532
Light loams	2	$2.767 \times 10^{-7}$	$2.710 \times 10^{-7}$	0.277	0.351	0.575
Textural classes after Dolgov						
Medium loams	11	$2.171 \times 10^{-7}$	$1.870 \times 10^{-7}$	0.365	0.562	0.687
Heavy loams	27	$2.250 \times 10^{-7}$	$2.003 \times 10^{-7}$	0.367	0.462	0.669
Light clays	6	$1.303 \times 10^{-7}$	$2.429 \times 10^{-7}$	0.393	0.316	0.766
Medium clays	13	$0.998 \times 10^{-7}$	$1.735 \times 10^{-7}$	0.358	0.326	0.845
Textural classes after Kachinskii						
Medium loams	21	$2.118 \times 10^{-7}$	$1.895 \times 10^{-7}$	0.383	0.529	0.659
Heavy loams	18	$2.304 \times 10^{-7}$	$2.072 \times 10^{-7}$	0.366	0.465	0.688
Light clays	17	$1.108 \times 10^{-7}$	$1.877 \times 10^{-7}$	0.364	0.306	0.760
Medium clay	1	$0.989 \times 10^{-7}$	$2.114 \times 10^{-7}$	0.343	0.279	0.990
All samples						
–	77	$2.506 \times 10^{-7}$	$1.469 \times 10^{-7}$	0.287	0.474	0.554

to be the largest for sands, sandy loams and light loams (Fig. 1), and it seems to be the lowest for medium clay according to the Dolgov's classification (Fig. 2). However, the dimensionless indices of agreement for sands (0.71 and 0.67 for loose and dense sand and turned out to be similar to those for medium and heavy loams (0.69 and 0.67 according to the Dolgov's classification and 0.66 and 0.69 according to the Kachinskii's classification). The smallest indices of agreement indices were obtained for sandy loams and light loams (0.53 and 0.58), and the greatest ones, for light and medium clays (0.77 and 0.85) defined according to Dolgov and 0.76 for light clays defined according to Kachinskii. The general average curve developed on the basis of all the available data demonstrates a great scatter of experimental datapoints (Fig. 2) and a low index of agreement equal to 0.55 (Table 2).

To obtain the Willmott's index of agreement, the sum of deviations of observed data from the model curve is divided by the sum of experimental data deviations from the model. Thus, the index of agreement compares errors in thermal diffusivity estimation by the average curve  $\kappa(\theta)$  for a certain textural class (or a general curve for the entire dataset) and the experimental data scattering within the same class (or the entire dataset). The accuracy of thermal diffusivity estimation on the basis of average curve parameters from Table 2 is actually compared to the representativeness of individual experimental dependences  $\kappa(\theta)$  in respect to the data for the considered textural class. Therefore, the dimensionless index of agreement depends on the number of samples and the standardized scatter of experimental data ignoring the changes

in the average thermal diffusivity upon the transition from class to class. This allows comparing the accuracy of calculated curves for various textural classes including those obtained using different classifications.

The average curves for sandy loams and light loams obtained from a very small number of samples (4 and 2) show the smallest index of agreement. At the same time, the average curve for the most numerous (27) heavy loam samples according to the Dolgov's classification is characterized by the index of agreement index equal to 0.67, which is significantly smaller than the indices of agreement for light and medium clays according to the same classification (0.77 and 0.85), though the number of samples in the two latter classes was substantially smaller. This comparison proves that an increase in the amount of experimental data improves the quality of the model curve just to a certain threshold. For the case of high variability of thermal diffusivity within the dataset, the model errors based on the average curve will be inevitably high. That is why, the index of agreement of the average curve developed using all the available data is so small.

Let us compare the indices of agreement obtained for textural classes identified according to Dolgov and Kachinskii. Thermal diffusivity estimates using parameters  $\kappa_0$ ,  $a$ ,  $\theta_0$ ,  $b$  from Table 2 for each class and application of equation (2) to all pairs  $P_i - O_i$  from all textural classes allowed obtaining the indices of agreement equal to 0.699 for the Dolgov's classification and 0.688 for the Kachinskii's classification. Note that only one sample of medium clay was identified using the Kachinskii's classification; and the index of agree-

ment between the estimated and experimental values of thermal diffusivity was nearly 1 for this sample. This is due to the fact that in this case the one-sample direct fit curve with minimal deviations from the experimental datapoints was used instead of the average curve for the textural class. However, even when these very small errors were used to calculate the resulting index of agreement index for the entire dataset, this index turned to be slightly smaller than that obtained for the Dolgov's classification. This may be explained by uniting dissimilar samples into one light clay class when using the Kachinskii's classification; whereas under the Dolgov's classification these samples were divided into two classes of light and medium clays with a smaller scatter of experimental data within each class and greater indices of agreement between the average curve and the experimental data.

To sum up, we may conclude that the accuracy of the general average curve  $\kappa(\theta)$ , developed using all the data available for 77 samples, was rather small. The index of agreement between this curve and the experimental datapoints was only 0.55. Grouping soils by texture and developing the average curves for each textural class significantly improved the accuracy of estimations. The general index of agreement between the experimental data and the set of average curves grew up to 0.70 when using the Dolgov's classification and up to 0.69 when using the Kachinskii's classification.

The dataset splitting according to the Kachinskii's classification based on the additional qualitative feature, i.e., the soil formation type, did not improve the accuracy of soil thermal diffusivity estimates as compared to the dataset splitting according to the Dolgov's classification. The similarity of indices of agreement obtained for two variants of textural splitting proves the acceptability of both textural classifications when modeling soil thermal diffusivity. However, the Dolgov's classification requires less input data and is based on the single quantitative indicator, i.e., the physical clay content. Hence, we recommend using the Dolgov's classification to estimate soil thermal diffusivity from the textural class name.

## CONCLUSIONS

The parameters of the dependence between the thermal diffusivity of mineral soils and their moisture content were obtained for eight textural classes including loose sand, dense sand, sandy loam, light loam, medium loam, heavy loam, light clay, and medium clay. To estimate soil thermal diffusivity, one should know soil textural class and soil moisture content.

To identify the soil textural class name, it is possible to use both the Kachinskii's classification (which considers the type of soil formation) and the Dolgov's classification (based on the physical clay content only).

The indices of agreement between the experimental data and the calculated values of thermal diffusivity, obtained using the two considered textural classi-

fications almost coincide. It is preferable to use the Dolgov's classification as it excludes possible mistakes in identifying the soil formation type.

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## REFERENCES

1. P. I. Andrianov, "Heat capacity of bound water and heat capacity of soils," *Dokl. Vses. Akad. S-kh. Nauk im. V.I. Lenina*, No. 2, 71–74 (1936).
2. T. A. Arkhangel'skaya, "A new empirical formula for estimating soil thermal diffusivity," in *Materials of the Scientific Session on Fundamental Soil Science, November 30–December 2, 2004, Moscow*, 2004, pp. 45–46.
3. T. A. Arkhangel'skaya, "Parameterization and mathematical modeling of the dependence of soil thermal diffusivity on the water content," *Eurasian Soil Sci.* **42**, 162–172 (2009).
4. T. A. Arkhangel'skaya, "Thermal diffusivity of gray forest soils in the Vladimir Opolie region," *Eurasian Soil Sci.* **37**, 285–294 (2004).
5. T. A. Arkhangel'skaya, M. A. Butylkina, M. A. Mazirov, and M. V. Prokhorov, "Properties and functioning of arable soils of the paleocryogenic soil complex in the Vladimir opolie region," *Eurasian Soil Sci.* **40**, 237–246 (2007).
6. T. A. Arkhangel'skaya, A. K. Guber, M. A. Mazirov, and M. V. Prokhorov, "The temperature regime of heterogeneous soilscape in Vladimir Opol'e region," *Eurasian Soil Sci.* **38**, 734–744 (2005).
7. T. A. Arkhangel'skaya, K. I. Luk'yashchenko, and P. I. Tikhonravova, "Thermal diffusivity of typical chernozems in the Kamennaya Steppe reserve," *Eurasian Soil Sci.* **48**, 177–182 (2015).
8. A. D. Voronin, *Fundamentals of Soil Physics* (Moscow State Univ., Moscow, 1986) [in Russian].
9. A. P. Geraizade, "Linear dependence of thermal diffusivity on the mechanical composition of soils," *Pochvovedenie*, No. 10, 120–123 (1974).
10. V. N. Dimo, "Dependence between thermal diffusivity and moisture of soils," *Pochvovedenie*, No. 12, 729–734 (1948).
11. E. A. Dmitriev, "Key factors of the specific heat capacity of the solid soil phase," *Vestn. Mosk. Univ.*, Ser. 16: Biol., No. 4, 103–111 (1958).
12. E. A. Dmitriev, "Regularities determining the value and changes in the specific heat capacity of the mineral anhydrous part of soils and rocks," *Vestn. Mosk. Univ.*, Ser. 16: Biol., No. 3, 79–84 (1959).
13. *Agrophysical Methods of Soil Studies*, Ed. by S. I. Dolgov (Nauka, Moscow, 1966) [in Russian].
14. N. A. Kachinskii, *Mechanical and Microaggregate Compositions of Soil and Their Analysis* (Academy of Sciences of USSR, Moscow, 1958) [in Russian].
15. K. I. Luk'yashchenko, Candidate's Dissertation in Biology (Moscow, 2012).
16. K. I. Lukiashchenko and T. A. Arkhangel'skaya, "Modeling thermal diffusivity of differently textured soils," *Eurasian Soil Sci.* **51**, 183–189 (2018).
17. K. I. Luk'yashchenko, T. A. Arkhangel'skaya, and A. B. Umarova, "Thermal diffusivity of plowed leached

- meadow-chernozemic soils in the Adygeya Republic," *Eurasian Soil Sci.* **45**, 404–407 (2012).
18. S. M. Skuratov, "Heat capacity of bound water," *Kolloidn. Zh.* **13** (5), 396 (1951).
  19. P. I. Tikhonravova and A. S. Frid, "Mathematical models of thermal diffusivity in solonetz soils in the Trans-Volga region of Volgograd oblast," *Eurasian Soil Sci.* **41**, 190–201 (2008).
  20. P. I. Tikhonravova and N. B. Khitrov, "Estimation of thermal diffusivity in Vertisols of the Central Cis-Caucasus region," *Eurasian Soil Sci.* **36**, 313–322 (2003).
  21. E. V. Shein and L. O. Karpachevskii, *Theories and Methods of Soil Physics* (Moscow, 2007) [in Russian].
  22. N. H. Abu-Hamdeh, "Thermal properties of soils as affected by density and water content," *Biosyst. Eng.* **86** (1), 97–102 (2003).
  23. T. Arkhangelskaya and K. Lukyashchenko, "Estimating soil thermal diffusivity at different water contents from easily available data on soil texture, bulk density, and organic carbon content," *Biosyst. Eng.* **168**, 83–95 (2018).
  24. D. Barry-Macaulay, A. Bouazza, B. Wang, and R. M. Singh, "Evaluation of soil thermal conductivity models," *Can. Geotech. J.* **52** (11), 1892–1900 (2015). <https://doi.org/10.1139/cgj-2014-0518>
  25. J. Busby, "Thermal conductivity and diffusivity estimations for shallow geothermal systems," *Q. J. Eng. Geol. Hydrogeol.* **49** (2), 138–146 (2016).
  26. J. Côte and J.-M. Konrad, "A generalized thermal conductivity model for soils and construction materials," *Can. Geotech. J.* **42**, 443–458 (2005).
  27. D. A. De Vries, "Thermal properties of soils," in *Physics of Plant Environment*, Ed. by W. R. van Wijk (North Holland, Amsterdam, 1963), pp. 210–235.
  28. Z. Gao, B. Tong, R. Horton, A. Mamtamin, Y. Li, and L. Wang, "Determination of desert apparent thermal diffusivity using a conduction-convection algorithm," *J. Geophys. Res.: Atmos.* **122**, 9569–9578 (2017). <https://doi.org/10.1002/2017JD027290>
  29. H. He, M. F. Dyck, R. Horton, K. L. Bristow, J. Lv, and B. Si, "Development and application of the heat pulse method for soil physical measurements," *Rev. Geophys.* **56**, (2018). <https://doi.org/10.1029/2017RG000584>
  30. J. Noilhan and S. Planton, "A simple parameterization of land surface processes for meteorological models," *Mon. Weather Rev.* **117**, 536–549 (1989).
  31. Y. Pachepsky and Y. Park, "Saturated hydraulic conductivity of US soils grouped according to textural class and bulk density," *Soil Sci. Soc. Am. J.* **79** (4), 1094–1100 (2015).
  32. Ya. A. Pachepsky and W. J. Rawls, "Accuracy and reliability of pedotransfer functions as affected by grouping soils," *Soil Sci. Soc. Am. J.* **63**, 1748–1757 (1999).
  33. R. J. Parikh, J. A. Havens, and H. D. Scott, "Thermal diffusivity and conductivity of moist porous media," *Soil Sci. Soc. Am. J.* **43**, 1050–1052 (1979).
  34. C. D. Peters-Lidard, E. Blackburn, X. Liang, and E. F. Wood, "The effect of soil thermal conductivity parameterization on surface energy fluxes and temperatures," *J. Atmos. Sci.* **55**, 1209–1224 (1998).
  35. M. S. Roxy, V. B. Sumithranand, and G. Renuka, "Variability of soil moisture and its relationship with surface albedo and soil thermal diffusivity at Astronomical Observatory, Thiruvananthapuram, south Kerala," *J. Earth Syst. Sci.* **119** (4), 507–517 (2010).
  36. M. G. Schaap, F. J. Leij, and M. Th. van Genuchten, "ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions," *J. Hydrol.* **251**, 163–176 (2001).
  37. J. Simunek, M. Th. van Genuchten, and M. Šejna, "Recent developments and applications of the HYDRUS computer software packages," *Vadoze Zone J.*, (2016). <https://doi.org/10.2136/vzj2016.04.0033>
  38. V. R. Tarnawski, T. Momose, and W. H. Leong, "Assessing the impact of quartz content on the prediction of soil thermal conductivity," *Géotechnique* **59** (4), 331–338 (2009).
  39. Z. Tian, Y. Lu, R. Horton, and T. Ren, "A simplified de Vries-based model to estimate thermal conductivity of unfrozen and frozen soil," *Eur. J. Soil Sci.* **67** (5), 564–572 (2016). <https://doi.org/10.1111/ejss.12366>
  40. B. Tong, Z. Gao, R. Horton, and L. Wang, "Soil apparent thermal diffusivity estimated by conduction and by conduction-convection heat transfer models," *J. Hydrometeorol.* **18**, 109–118 (2017). <https://doi.org/10.1175/JHM-D-16-0086.1>
  41. B. Usowicz and Ł. Usowicz, "Thermal conductivity of soils—comparison of measured results and estimation methods," in *Proceedings of Eurosoil 2004 Congress, September 4–12, 2004 Freiburg, Germany, Abstracts of Papers* (Freiburg, 2004). [http://www.bodenkunde2.uni-freiburg.de/eurosoil/abstracts/id795\\_Usowicz\\_full.pdf](http://www.bodenkunde2.uni-freiburg.de/eurosoil/abstracts/id795_Usowicz_full.pdf).
  42. K. van Looy, J. Bouma, M. Herbst, J. Koestel, B. Minasny, U. Mishra, C. Montzka, A. Nemes, Y. A. Pachepsky, J. Padarian, M. G. Schaap, B. Tóth, A. Verhoef, J. Vanderborght, M. J. van der Ploeg, et al., "Pedotransfer functions in Earth system science: challenges and perspectives," *Rev. Geophys.* **55**, (2017). <https://doi.org/10.1002/2017RG000581>
  43. C. J. Willmott, S. M. Robeson, and K. Matsuura, "A refined index of model performance," *Int. J. Climatol.* **32**, 2088–2094 (2012).
  44. X. Xie, Y. Lu, T. Ren, and R. Horton, "An empirical model for estimating soil thermal diffusivity from texture, bulk density, and degree of saturation," *J. Hydrometeorol.* **19**, 445–457 (2018).

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