Thermal Properties of Representative Soils of the Czech Republic

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Abstract

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Knowledge of soil thermal properties is essential when assessing heat transport in soils. Thermal regime of soils is associated with many other soil processes (water evaporation and diffusion, plant transpiration, contaminants behaviour etc.). Knowledge of thermal properties is needed when assessing effectivity of energy gathering from soil profiles using horizontal ground heat exchangers, which is a topic of our research project. The study is focused on measuring of thermal properties (thermal conductivity and heat capacity) of representative soils of the Czech Republic. Measurements were performed on soil samples taken from the surface horizons of 13 representative soil types and from 4 soil substrates, and on mulch (bark chips) sample using KD2 PRO device with TR-1 and SH-1 sensors. The measured relationships between the thermal conductivity and volumetric soil-water content were described by the non-linear equations and those between the volumetric heat capacity and volumetric soil-water content were expressed using the linear equations. The highest thermal conductivities were measured in soils on quartz sand substrates. The lowest thermal conductivities were measured in the Stagnic Chernozem Siltic on marlite and the Dystric Cambisol on orthogneiss. The opposite trend was observed for maximal heat capacities, i.e. the highest values were measured in the Stagnic Chernozem Siltic and the lowest in sand and soils on sand and sandy gravel substrate.

Keywords: heat capacity; laboratory measurements; sensor comparison; soil thermal properties; soil-water content; soil types; thermal conductivity

Soil profiles and ground beneath soil profiles became a very popular source of energy used for building heating. Effective energy gathering using horizontal ground heat exchangers is controlled by a thermal regime around (mostly above) exchangers. Heat transport within the soil profile (e.g. heat accumulation during the warm season and heat discharge during the cold season) is coupled with water flow. Both transport processes may be assessed experimentally and mathematically. There are numerous models applicable for simulating both processes (a.o. Saito *et al.* 2006; Vogel *et al.* 2011).

To use these models, the soil hydraulic and thermal properties must be known. Properties may be either measured or estimated. Soil hydraulic properties (i.e. soil-water retention and hydraulic conductivity curves) may be estimated for instance from some basic soil properties using pedotransfer functions (Wösten *et al.* 1999) modified for Czech soils by Miháliková *et al.* (2013). Soil thermal properties (volumetric heat capacity and thermal conductivity) may be also estimated. Soil volumetric heat capacity is usually assumed to be a sum of volumetric heat capacities of each soil components (mineral grains, organic matter, water, ice, air) multiplied by their fractions. Tables 1 and 2 show specific densities, specific heats, volumetric heat capacities for selected soil components and selected rocks. The linear relationship between the volumetric heat capacity and soil-water content, $C(\theta)$, is expected. Various approaches were proposed to describe/estimate the relationship between thermal conductivity and soil-water content. Thermal conductivity of any component mixture may be expressed as weighted sum of thermal conductivities of all components (de Vries 1963). Thermal conductivities of various soil components are given in Table 3. Weights related to soil components were summarized by Campbell *et al.* (1994). Thermal conductivity increases with rising temperature (Campell *et al.* 1994; Smits *et al.* 2013). The nonlinear relationships between thermal conductivity and soil-water content, $\lambda(\theta)$, are usually assumed (Campbell 1985; Chung & Horton 1987; Côté & Konrad 2005). Some models, however, assume a simple linear $\lambda(\theta)$ relationship (Loukili *et al.* 2008). Empirical parameters presented in different expressions (which may be also evaluated via fitting experimental $\lambda(\theta)$ data using particular expression) are usually set at values proposed for only few soils. Estimates are mostly based on soil texture classes and organic matter content. Some expressions also include average thermal conductivity of mineral grains and thermal conductivities of organic matter content and water. Votrubová *et al.* (2012) studied the impact of different estimates of $\lambda(\theta)$ relationship on simulated thermal regime in the soil profile. They found that differences between the simulated soil temperatures were small, but the surface soil heat fluxes were substantially different.

An accurate description of heat fluxes in soil is essential particularly for assessing efficiency of the horizontal ground heat exchangers. Therefore the objective of our study was to evaluate and summarize thermal properties of representative soils of the Czech Republic to provide a set of parameters, which may be used for simulating thermal regime in soils not only near the heat exchangers.

Table 1. Density, specific heat, and volumetric heat capacity of common soil components at 20°C and 0.101 MPa (van Wijk & de Vries 1963)

Soil component	Density (Mg/m^3)	Specific heat (kJ/kg/K)	Volumetric heat capacity (MJ/m^3/K)
Soil minerals (average)	2.65	0.73	1.9
Soil organic matter (average)	1.30	1.9	2.5
Water	1.00	4.18	4.18
Ice (0°C)	0.92	2.0	1.9
Air	0.0012	1.0	0.0012

Table 2. Density, specific heat, and volumetric heat capacity of selected rocks at 20°C (selected data from Clauser 2011)

Rock	Density (Mg/m^3)	Specific heat (kJ/kg/K)	Volumetric heat capacity (MJ/m^3/K)
Amphibole	3.01	0.70–1.13	2.110–3.410
Basalt	2.87	0.88–0.90	2.526–2.583
Dolomite	2.8	0.90	2.520
Clay	2.68	0.86	2.300
Gneiss	2.70	0.77–0.98	2.080–2.640
Gypsum	2.37	1.01	2.930
Granite	2.62–2.65	0.60–1.17	1.590–3.070
Limestone	2.76–2.77	0.68–0.88	1.880–2.430
Quartzite	2.64	0.73–1.01	1.930–2.670
Sandstone	2.64	0.775	2.050
Schist	2.77–2.90	0.79–1.09	2.190–3.180
Siltstone	2.68	0.91	2.449
Slate	2.77–2.78	0.74–1.11	2.060–3.080
Syenite	2.82	0.460	1.300

Table 3. Thermal conductivities (in W/m/K) of soil related materials (Bristow 2002) (T in °C)

Material	Thermal conductivity
Basalt	2.2
Granite	2.0
Quartz	8.8
Clay minerals	2.9
Organic matter	0.25
Water	$0.552 + 2.34 \times 10^{-3}\,T - 1.1 \times 10^{-5}\,T^2$
Air	$0.0237 + 0.000064\,T$
Ice (0°C)	2.18

METHODS

Seventeen soils (13 samples from humic horizons of various soil types and 4 substrates) occurring in the Czech Republic (Table 4) were selected to study the relationships between the soil thermal properties (heat capacity and thermal conductivity) and soil water content. The same soils (11 samples from humic horizons and 2 substrates) were previously used to assess various pesticides adsorption in the representative soils of the Czech Republic (Kodešová *et al*. 2011a). The basic soil properties (Table 4) were determined using standard laboratory techniques (Kodešová *et al*. 2011a). Bark chips, which are used for soil top mulching, were also tested.

The KD2 Pro device, a portable field and laboratory thermal properties analyzer, was used to measure thermal properties in the laboratory (Anonymous 2006). The device includes 3 sensors – KS-1, TR-1, and SH-1. KS-1 is a single-needle sensor, which is 60 mm long and 1.3 mm in diameter. This sensor is designed primarily for liquid samples and insulating materials. TR-1 is also a single-needle sensor 100 mm long and 2.4 mm in diameter. It is designed primarily for soil, concrete, rock, and other granular or solid materials (it should not be used to measure liquid samples due to the large heat pulse). Both sensors measure thermal conductivity and resistivity (inverse value of conductivity). SH-1 is a dual-needle sensor (30 mm long, 1.3 mm diameter, 6 mm spacing) for measuring thermal conductivity, resistivity, heat capacity, and thermal diffusivity (ratio between thermal conductivity and capacity). It is designed for most solid and granular materials, but should not be used in liquids. Both sensors applicable for soils (TR-1 and SH-1) were used in our study.

Experiments were performed under 20°C laboratory conditions. The soils, which were air-dried and sieved through a 2-mm sieve, were packed into plastic cylinders (volume of 423 cm^3, height of 11 cm) to obtain bulk densities (ρ_d) similar to values measured on undisturbed 100 cm^3 soil samples collected in the field. Two soil columns were prepared for each soil sample. The final average ρ_d (g/cm^3) values are presented in Table 4. Porosity, *P* (%), was calculated from the bulk density, ρ_d, and soil particle density, ρ_s (g/cm^3). It should be noted that soils were sampled when no crop was planted (except topsoil with permanent grass cover in Měcholupy). Root impact on thermal properties was eliminated in all cases. In the case of all Cambisols, fraction of soil particles larger than 2 mm was extracted. The main reason was that both sensors (particularly SH-1) would not be applicable in a coarser material.

Sensors (either TR-1 or SH-1) were inserted into the packed dry soils and thermal properties were measured. Each sensor was used and properties were measured at least twice. Measurements were repeated if the values from the first two measurements differed. Outliers were excluded and the average values from remaining ones were then calculated for each soil column. Soil samples were then gradually wetted and thermal properties measurements were repeated for soils of increasing soil water contents. Dry soils were taken out from the cylinders and wetted with 30 cm^3 of distilled water using a sprayer, homogenized, and then packed back into the cylinders (theoretical water content increment of approximately 0.07 cm^3/cm^3). Each soil sample was weighted immediately after packing to determine soil water content gravimetrically and soil thermal properties were measured. This procedure was repeated 3 times. Then the soil maintained in the column and the same amount of water was added on the soil surface and the samples were placed into the plastic bag for several hours to let water redistribute within the soil. After that the soil samples were weighted again and thermal properties were measured. The procedure was repeated until full water saturation of the soil samples was reached. Despite that known amount of water was applied, a gravimetric method, which is the only direct reference method, was used to determine volumetric soil water content. Assuming specific density of water (ρ_w) to be 1 g/cm^3, soil water content was evaluated as a ratio of mass of water (difference between mass of wet soil and mass of soil dried under 105°C) and a sample volume. It should be mentioned that the lower water content increment than theoretical was always registered

Table 4. Studied soils and their properties: soil texture, organic matter content, soil particle density (ρ_s), soil bulk density (ρ_d) and porosity (P) of tested columns

Soil type	Location	Soil substrate	Sand	Silt	Clay	Organic matter	ρ_s	ρ_d	P (%)	Textural class
			(%)				(g/cm^3)			
Stagnic Chernozem Siltic[a]	Milčice	marlite	29.5	54.6	15.8	5.03	2.23	1.35	39.5	silty loam
Haplic Chernozem[a]	Ivanovice na Hané	loess	13.2	75.5	11.4	3.05	2.48	1.48	40.3	silty loam
Haplic Chernozem[a]	Suchdol	loess	24.4	56.3	19.3	3.47	2.52	1.31	48.0	silty loam
Chernozem Arenic[a]	Velké Chvalovice	gravely sand	73.6	20.0	6.4	1.59	2.56	1.6	37.5	sandy loam
Greyic Phaeozem[a]	Čáslav	loess	9.5	77.1	13.4	2.33	2.51	1.47	41.4	silty loam
Haplic Luvisol[a]	Hněvčeves	loess	9.6	76.5	13.9	1.78	2.43	1.42	41.6	silty loam
Haplic Cambisol[a]	Humpolec	paragneiss	55.4	34.7	9.9	2.82	2.39	1.35	43.5	sandy loam
Haplic Cambisol[a]	Předbořice	syenite	59.0	36.2	4.8	2.95	2.77	1.48	46.6	sandy loam
Haplic Cambisol[a]	Jince	quartzite	35.9	43.7	20.3	2.78	2.75	1.51	45.1	loam
Haplic Cambisol	Tábor	paragneiss	60.4	26.9	12.6	3.97	2.56	1.25	51.1	loamy sand
Dystric Cambisol[a]	Vysoké nad Jizerou	orthogneiss	25.3	57.8	16.9	3.99	2.64	1.34	49.2	silty loam
Arenosol Epieutric[a]	Semice	sand	83.7	12.8	3.5	1.14	2.52	1.8	28.6	loamy sand
Loess[a]	Suchdol	–	23.7	51.8	24.5	0.76	2.53	1.37	45.9	silty loam
Sand[a]	Písková Lhota	–	93.7	3.0	3.3	0.04	2.83	1.71	39.6	sand
Weathered paragneiss	Tábor	–	76.2	18.3	5.5	0.34	2.66	1.37	48.5	sand
Technosol – topsoil	Měcholupy	slate and siltstone[b]	12.2	60.5	27.3	1.86	2.63	1.38	47.4	clay loam
Technosol – subsoil	Měcholupy	slate and siltstone[b]	49.4	37.1	13.5	1.33	2.69	1.46	45.9	sandy loam
Mulch – bark chips	–	–	–	–	–	100	1.66	0.23	86.1	–

[a]soils and data evaluated by Kodešová *et al.* (2011a); [b]assuming that soil horizons of the Technosol were formed of the material collected at this area (i.e. deposited topsoil, which was removed before starting construction works, and redeposited subsoil material during and after construction mixed with construction waste)

due to water loses when spraying water on the soil surface and/or homogenizing the soil sample. The applied method followed the procedure for calibrating soil water content sensors published by Kodešová *et al.* (2011b). Mulch (bark chips) was also air dried and then carefully disintegrated into small fragments. To obtain its thermal properties, the same procedure like by the soils was applied.

Analytical expressions were used to describe relationships between the thermal properties and soil water contents. Measured relationships (data points) obtained always from two soil columns (which in all cases closely matched each other) were fitted using a single equation. The measured relationships between thermal conductivity, λ ($ML/T^3/K$), and volumetric soil-water content, θ (L^3/L^3), were described by the non-linear equation (Chung & Horton 1987)

$$\lambda(\theta) = b_1 + b_2\theta + b_3\theta^{0.5} \quad (1)$$

where:

b_1, b_2, b_3 – empirical parameters ($ML/T^3/K$)

The measured relationships between the volumetric heat capacity, C ($M/L/T^2/K$), and volumetric soil water content, θ (L^3/L^3), were expressed assuming that the volumetric heat capacity may be estimated using the following equation:

$$C = f_pC_p + f_oC_o + C_w\theta = f_sC_s + C_w\theta \quad (2)$$

where:

f – fractions of soil components (L^3/L^3)

p, o, s, w – denoting mineral soil particles, organic matter, solid, and water, respectively

The C values presented in Table 1 are usually used for predicting volumetric heat capacity of soils. The following linear equation was used to fit the measured data:

$$C = a + b\theta \quad (3)$$

where:

$$a = f_sC_s, \quad b = C_w \quad (4)$$

The volumetric heat capacity, C_s ($M/L/T^2/K$), of solid was then calculated as follows:

$$C_s = \frac{a}{(1 - P/100)} \quad (5)$$

RESULTS AND DISCUSSION

Parameters b_1, b_2, and b_3 of Eq. (1) (describing the λ(θ) relationship) obtained from data measured using sensors TR-1 and SH-1 are shown in Table 5. According the sensor parameters (Anonymous 2006), lower accuracy of sensor TR-1 than of sensor HS-1 is expected. The measured values of thermal conductivities were, however, mostly similar. Sensor TR-1 consistently measured slightly higher λ values than sensor SH-1. Therefore different b_1, b_2, and b_3 parameters were evaluated. Slightly different shapes of the thermal conductivity curves evaluated using both sensors are shown in Figure1. Figure 1 also shows thermal conductivities calculated using Eq. (1) and parameters b_1, b_2 and b_3 (in W/m/K) proposed by Chung & Horton (1987) for different textures: sand $b_1 = 0.228$, $b_2 = -2.406$, $b_3 = 4.909$; silt $b_1 = 0.243$, $b_2 = 0.393$, $b_3 = 1.534$; clay $b_1 = -0.197$, $b_2 = -0.962$, $b_3 = 2.521$. These estimates were used in many studies (a.o. Buchner *et al.* 2008; Sakai *et al.* 2011; Bauer *et al.* 2012; Votrubová *et al.* 2012).

The highest thermal conductivities were measured on sandy soils (Arenosol Epieutric on sand and Chernozem Arenic on gravely sand substrate) and sand. This is given by quartz present in these samples (thermal conductivity of quartz is approximately 3–4 times higher than that of other soil components, Table 3). Thermal conductivity curves differed in shape. Initial steep increase of λ values with increasing soil water content and consequent curve relaxation was observed for sand with the highest sand fraction and little organic matter. Initial curve slope for other two soils decreased with decreased sand fraction and increased organic matter content. However, in all cases similar and considerably high values were measured for full saturation (the soil water contents corresponded to the highest λ values in Figure 1). This may be explained by the isolation effect of the organic matter and clay particles for lower θ values. The thermal conductivity curve estimated using Chung and Horton (1987) parameters for sand noticeably differed from the curves of both topsoils (Arenosol Epieutric and Chernozem Arenic), which may again be associated with organic matter and clay fractions.

Considerably lower λ values were measured in soils on loess substrates and loess. The thermal conductivity curves moderately differed. Thermal conductivities rose with increasing values of soil bulk density and decreasing organic matter content. The thermal conductivity curve estimated using parameters for silt reported by Chung and Horton (1987) was within the range of data for all 5 samples measured using TR-1 sensor and slightly above the range of data measured for low soil water contents using SH-1 sensor.

Table 5. Parameters b_1, b_2, and b_3 (W/m/K) of Eq. (1) describing relationships between soil water content, θ (cm³/cm³), and heat conductivity, λ (W/m/K), and parameters a and b (MJ/m³/K) of Eq. (3) describing relationships between soil water content, θ (cm³/cm³), and heat capacity, C (MJ/m³/K), and the volumetric heat capacity, C_s (MJ/m³/K), of solid

Soil type	Location	No. of fitted data-points[a]	Sensor TR-1				Sensor SH-1				Sensor SH-1			
			b_1	b_2	b_3	R^2	b_1	b_2	b_3	R^2	a	b	R^2	C_s
Stagnic Chernozem Siltic	Milčice	8+8	0.197	1.288	0.866	0.934	0.160	1.868	0.383	0.968	1.187	5.138	0.982	1.962
Haplic Chernozem	Ivanovice na Hané	7+7	0.274	2.181	0.747	0.959	0.194	2.515	0.442	0.969	1.187	5.496	0.971	1.988
Haplic Chernozem	Suchdol	7+7	0.195	1.217	0.973	0.960	0.184	2.423	0.248	0.986	1.087	4.922	0.980	2.090
Chernozem Arenic	Velké Chvalovice	6+6	0.237	5.612	1.898	0.946	0.263	7.505	–0.132	0.981	1.173	5.020	0.921	1.877
Greyic Phaeozem	Čáslav	8+8	0.228	0.280	1.708	0.958	0.199	1.755	0.925	0.964	1.168	4.569	0.961	1.993
Haplic Luvisol	Hněvčeves	7+7	0.238	1.033	1.673	0.945	0.216	1.982	0.969	0.971	1.123	4.835	0.966	1.923
Haplic Cambisol	Humpolec	7+7	0.212	1.275	1.104	0.965	0.186	1.872	0.683	0.957	1.221	4.726	0.951	2.161
Haplic Cambisol	Předbořice	7+7	0.239	1.558	1.066	0.977	0.199	2.312	0.412	0.979	1.168	4.889	0.971	2.187
Haplic Cambisol	Jince	7+7	0.259	1.961	1.063	0.956	0.204	2.469	0.615	0.976	1.308	4.472	0.963	2.383
Haplic Cambisol	Tábor	9+9	0.205	1.155	1.234	0.979	0.173	1.350	1.160	0.959	1.054	5.139	0.945	2.155
Dystric Cambisol	Vysoké nad Jizerou	8+8	0.225	1.206	0.799	0.975	0.177	1.304	0.663	0.981	1.233	4.506	0.984	2.427
Arenosol Epieutric	Semice	5+5	0.352	4.481	3.761	0.979	0.259	8.990	0.871	0.990	1.314	5.293	0.958	1.840
Loess	Suchdol	7+7	0.225	1.876	0.955	0.952	0.193	2.191	0.618	0.945	1.140	4.934	0.948	2.107
Sand	Písková Lhota	6+6	0.319	–6.709	7.825	0.990	0.286	–2.654	5.340	0.975	1.307	3.621	0.962	2.164
Weathered paragneiss	Tábor	9+9	0.268	1.009	1.163	0.9745	0.213	1.076	1.128	0.957	1.207	4.324	0.959	2.344
Technosol – topsoil	Měcholupy	7+7	0.317	1.586	0.959	0.845	0.254	2.204	0.493	0.917	1.363	4.987	0.949	2.591
Technosol – subsoil	Měcholupy	7+7	0.299	0.819	1.626	0.865	0.231	1.547	1.213	0.877	1.394	4.089	0.976	2.577
Mulch – bark chips	-	18	0.020	0.579	0.164	0.961	0.096	0.739	-0.140	0.957	0.413	4.274	0.951	2.971

[a]two columns for each soil sample, one column for mulch

Thermal conductivities measured in all Cambisols were similar to those measured in soils on loess. The lowest λ value was observed for Dystric Cambisol (on orthogneiss). Higher values were obtained in both Haplic Cambisols on paragneiss (Humpolec and Tábor) and weathered paragneiss (Tábor). Interestingly, very similar data were obtained for all 3 soil samples despite the fact that weathered paragneiss contained a very little organic matter. Slightly higher values were measured for the Haplic Cambisol on

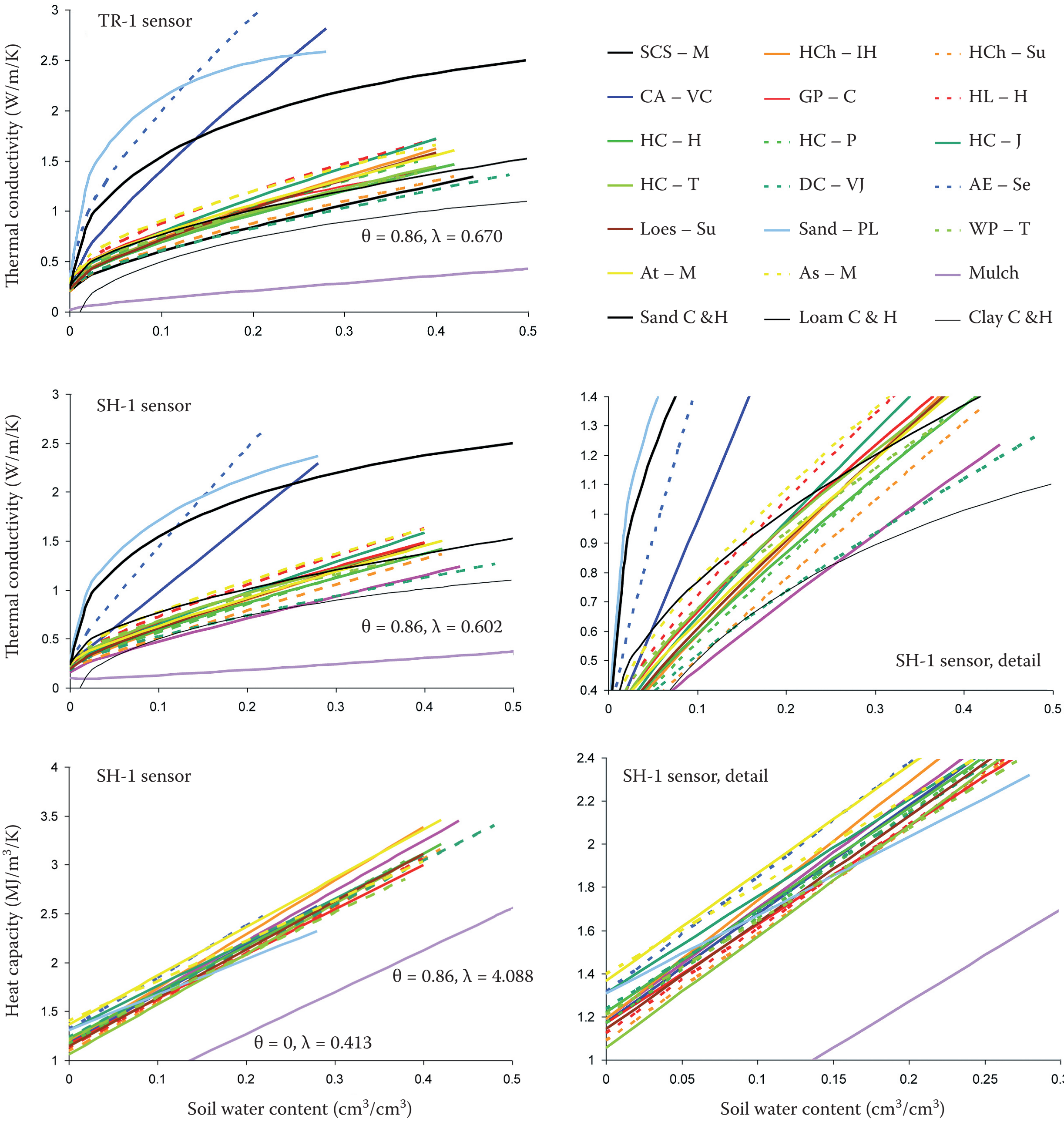

Figure 1. Fitted soil thermal properties for: SCS – M (Stagnic Chernozem Siltic – Milčice), HCh – IH (Haplic Chernozem – Ivanovice na Hané), HCh – Su (Haplic Chernozem – Suchdol), CA – VC (Chernozem Arenic – Velké Chvalovice), GP – C (Greyic Phaeozem – Čáslav), HL – H (Haplic Luvisol – Hněvčeves), HC – H (Haplic Cambisol – Humpolec), HC – P (Haplic Cambisol – Předbořice), HC – J (Haplic Cambisol – Jince), HC – T (Haplic Cambisol – Tábor), DC – VJ (Dystric Cambisol – Vysoké nad Jizerou), AE – Se (Arenosol Epieutric – Semice), Loess – Su (Suchdol), Sand – PL (Písková Lhota), WP – T (Weathered paragneiss – Tábor), At – M (Technosol – topsoil – Měcholupy), As – M (Technosol – subsoil – Měcholupy), Mulch (bark chips), Clay C&H, Loam C&H, Sand C&H (Chung & Horton 1987)

syenite and the highest values were measured on the Haplic Cambisol on quartzite. This was probably caused mostly by different mineral composition, which is indicated by the soil particle density.

Very low thermal conductivities were measured on the Stagnic Chernozem Siltic, which is associated with the mineral composition and a very high organic matter content (indicated by soil particle density and bulk density). Results are similar to those in the Dystric Cambisol (on orthogneiss) and to estimated data using Chung and Horton (1987) parameters for clay.

Results for both Technosol samples (derived probably from slate and siltstone) were similar to those for soils on loess. Results for mulch (bark chips) show very low thermal conductivities, i.e. isolative character of this material.

The results documented that real soil composition (not only textural classes) needs to be suggested when estimating thermal conductivities. Water in quartz sands causes connection of highly conductive particles (i.e. initial steep increase of thermal conductivity curve) (Bristow 2002), which is considerably less pronounced in soils containing other components and in other soils (containing low quartz fraction or none). Thermal conductivities of other sandy soils were within the range of data of remaining soils. Thus the curve expected for sandy material cannot be used for non-quartz sands or to describe properties of preferential flow domain in the dual-permeability model (Gerke & van Genuchten 1993) (as suggested by Votrubová *et al.* 2012), which from the water flow viewpoint is assumed to have properties of coarse sands. The general organic matter influence (i.e. deceasing impact on λ values) should be expected based on the low thermal conductivity of this soil component (Table 3). For instance a new parameterization for grassland soils was proposed by Chen *et al.* (2012).

It should be noticed that curves calculated using Eq. (1) in some cases did not precisely follow the measured S-shaped curves, which was indicated by R^2 values (Table 5). We have found out that the better fits of some λ(θ) relationships would be obtained using a degree 3 polynomial (not shown). However, such a function would not be applicable to most available mathematical models and probably would not considerably increase accuracy of the simulated soil thermal regimes.

Figure 1 and Table 5 also show heat capacity curves (i.e. linear relationship between the volumetric heat capacity(C), and the soil-water content (θ), measured using the sensor SH-1), resulting parameters a and b Eq. (3), and C_s values Eq. (5). Lines differ depending on soil composition (variable fractions of minerals and organic matter), which is according Eq. (2) included in a parameter, and water content. Resulting C_s values (calculated from a parameters) in many cases correspond to average value of volumetric heat capacity of soil minerals proposed by van Wijk and de Vries (1963) (Table 1). However, in many cases considerably greater values were obtained, which is probably associated with soil substrates (quartzite, gneiss, slate) of higher volumetric heat capacities (Table 2). (A very little impact of organic matter is expected due to small fractions of organic matter in the studied soil samples.) Thus it is apparent that particular mineral composition should be assumed as well when assessing soil heat capacity. It is also evident that the line slope is variable as well. The b parameter should be actually equal to volumetric heat capacity of water, which is 4.18 MJ/m^3/K (Table 1) (van Wijk & de Vries 1963). In our case the b parameter is mostly higher. It should be noted that volumetric heat capacity of water increases with temperature, but in our case temperature should not play any role since the experiments were performed at 20°C. In general, slightly higher (due to higher $b = C_w$ value) or moderately higher (due to higher C_s and b values) C values were measured than would be estimated using Eq. (2) and data in Table 1. The opposite trend (in comparison to thermal conductivities) was observed for maximal heat capacities. The highest C values were measured in the Stagnic Chernozem Siltic and the lowest C values in sand and soils on sand and sandy gravel substrates, which is associated with the amount of water stored in the soil sample.

It should be mentioned that parameters of soil thermal properties may be also estimated from soil temperatures monitored under laboratory or field conditions via parameters optimization using a proper numerical model for simulating heat transport coupled with water flow (a.o. HYDRUS models by Šimůnek *et al.* 2008) (Mortensen *et al.* 2006; Saito *et al.* 2007) or other mathematical techniques (Bateni *et al.* 2012).

CONCLUSION

Thermal properties of a set of representative soils of the Czech Republic were measured. The highest thermal conductivities were measured in soils on quartz sand substrates (which was a result of a considerably higher thermal conductivity of quartz than of other soil components). Thermal conductivity curve estimated using Chung and Horton (1987) parameters for sand noticeably differed from curves of topsoils on quartz sand substrates. The lowest thermal conductivities were measured in the Stagnic Chernozem Siltic on marlite and Dystric Cambisol on orthogneiss. The results were similar to estimated data using Chung and Horton (1987) parameters for clay. Thermal conductivities of other soils oscillated near values estimated using Chung and Horton (1987) parameters for silt.

An opposite trend was observed for maximal heat capacities, i.e. the highest *C* values were measured in the Stagnic Chernozem Siltic and the lowest in sand and soils on sand and sandy gravel substrate, which was caused by considerably different water saturation of the soils. In many cases, moderately higher *C* values were measured than would be estimated using the average values of volumetric heat capacities of soil components proposed by van Wijk and de Vries (1963).

The presented dataset will be further used for assessing heat exchangers efficiency in various soils of the Czech Republic. While soils of higher thermal conductivities ensure faster soil temperature recovery near heat exchangers, soils of higher heat capacities provide a larger heat storage. The future goal is regional characterization of soil and climate suitability for effective utilization of heat exchangers and their design under particular conditions. Presented data may be also used for evaluating soil thermal regimes associated with other soil processes.

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