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Thermal properties of Cambisols in mountain regions under different vegetation covers

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Abstract: Soil thermal properties regulate the thermal and water balance and influence the soil temperature distribution. The aim of the current study is to present data on the changes in the thermal properties of Cambisols at different ratios between the water content and the air in the pore space under different vegetation covers in mountain regions. The undisturbed soil samples were taken from the surface soil layers under grassland, deciduous and coniferous forests in three experimental stations of the Forest Research Institute – Gabra in Lozen Mountain, Govedartsi in Rila Mountain and Igralishte in Maleshevska Mountain. The soil thermal conductivity (λ), the thermal diffusivity (α) and the volumetric heat capacity (C_v) were measured with the SH-1 sensor of a KD2Pro device at different matric potentials in laboratory conditions. The thermal conductivity of the investigated soils was also measured with the TR-1 sensor of a KD2Pro device at the transitory soil moisture in field conditions. An increase in the thermal properties with the soil water content was best pronounced for λ and depended inversely on the total porosity. As the total porosity increased with the soil organic carbon content and decreased with the skeleton content, the lowest value of λ was established in the surface horizons of Dystric Cambisols (Humic) in the experimental station in Govedartsi. The soil thermal conductivity increased with the depth under the deciduous forest (Gabra and Igralishte) due to the lower soil organic carbon content (SOC) and the total porosity. There were no such changes in the subsurface horizon under the grassed associations. The increase in the heat capacity with the water content depended on the SOC to less extent. In the horizons with a SOC of less than 1.5%, the changes in the thermal diffusivity over the whole range of wetness were 1.7 times higher than those with a higher SOC.

Keywords: coniferous forest; deciduous forest; forest soils; grassland; KD2Pro device; soil thermal properties; soil water retention curve

The processes of mass and heat transfer in a soil are dynamic and depend on the volume of pores occupied by the water and air. Additionally, the presence of vegetation and the climate conditions also influence these processes. The thermal conductivity (λ), the volumetric heat capacity (C_v) and the thermal diffusivity (α) are the basic soil thermal properties as they determine the variation in the soil temperature in space and time, and regulate the heat and water balances. Most of the studies conducted in Bulgaria have been based on soil temperature data to evaluate the apparent soil thermal diffusivity under grassland

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(Marinova et al. 2007; Doneva 2011, 2016; Doneva & Kercheva 2017).

The volume fractions of water and air, the mineral composition and organic matter content in the soil affect its thermal properties. Additionally, λ depends on the size, the shape and the packing arrangements of the soil particles, i.e., on the soil structure (de Vries 1963). The effect of the bulk density (ρ_b), moisture content, salt concentration, and organic matter on λ of some sieved and repacked Jordanian soils was investigated in laboratory conditions (Abu-Hamdeh & Reeder 2000). Abu-Hamdeh (2003) studied the effect of the water content and ρ_b on the specific heat capacity (c), C_v and α of two soils classified as sand and clay. The clay soil had, in general, a higher c and C_v than the sandy soil for the same soil water content and density. It was concluded that the sandy soil exhibited a peak of α at a definite moisture content range unlike the clay soil. Such pronounced peak values of α (0.83–0.99 mm^2/s) were demonstrated for sandy soils at low water contents by Lebedev et al. (2019). Silva-Aguilar et al. (2018) reported that values of the apparent thermal diffusivity ranged between 0.23 and 0.87 mm^2/s for sandy soils.

According to Ochsner et al. (2001), the soil thermal properties are more strongly correlated with the volume fraction of air than the volume fractions of water (θ) and solids. The authors examined the relationships between the thermal properties of four medium textured soils and the volume fractions of soil, water, solids and air. It was concluded that λ could be accurately described as a decreasing linear function of the air-filled porosity (AP). The thermal properties as functions of θ, ρ_b and AP were studied by Tong et al. (2020). The authors concluded that the soil thermal property values and the soil AP exhibited simple linear relationships. The λ-AP linear relationship was verified by Xie et al. (2020) who pointed out that it could be applied potentially in land surface models for estimating λ from θ and ρ_b.

The development and verification of models for predicting the soil thermal properties require data on the *in situ* measured thermal properties. The KD2Pro (Decagon Devices 2016) is a compact, portable and appropriate device to directly measure the thermal properties in laboratory and field conditions (Smits et al. 2010, 2013, 2016; Kodešová et al. 2013; Rubio 2013, 2014; Doneva & Rubio 2015; Usowicz & Lipiec 2020 etc.). The thermal conductivity was measured with a KD2Pro device for sands under varied porosity and water content in drainage-wetting-drying cycles (Smits et al. 2010). The results showed that the λ-θ relationship was independent of whether the soil was going through wetting or drainage. Additionally, the effect of the temperature on λ and α was studied for sands with different mean grain sizes under varied water saturation levels (Smits et al. 2013). Smits et al. (2016) measured λ of sandy loam soils using a KD2Pro device in laboratory conditions in order to evaluate the impact of a forest fire on λ. The results showed that λ of the fire-heated soils was slightly lower than that of the control soils for all the observed water contents. The authors pointed out that the Campbell et al. (1994) model gave the best agreement over the full range of water contents. Campbell et al. (1994) presented data on λ measurements under high temperature conditions relevant to burning since burning is often used as a management tool by foresters. Kodešová et al. (2013) measured the thermal conductivity and the heat capacity of representative soils in the Czech Republic using a KD2Pro device with TR-1 and SH-1 sensors. The lowest λ values were measured in Stagnic Chernozem Siltic on marlite rocks and Dystric Cambisol on orthogneiss rocks. The opposite trend (in comparison to λ) was observed for the heat capacities, i.e., the highest C_v values were measured in Stagnic Chernozem Siltic and the lowest C_v values were measured in the sands and soils on sand and sandy gravel substrates, which was caused by considerably different water saturation of the soils.

The thermal conductivity and the thermal resistivity of an Alluvial-meadow soil (Fluvisol, according to FAO 2006) were measured with the SH-1 sensor of a KD2Pro device in a laboratory experiment and λ values were obtained for a wide range of water contents (Doneva & Rubio 2015).

The soils in mountain regions are characterised with varying structural characteristics due to the greater variations in the soil organic carbon content, the presence of rocks, and the types of vegetation cover. There is a lack of information on the effect of these different conditions on the soil thermal properties of Cambisols under adjacent different vegetation covers in mountain regions.

The aim of the current study is to quantify the changes in the thermal properties of Cambisols in mountain regions under different land use and at different ratios between the water content and the air in the pore space.

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MATERIAL AND METHODS

Nine soil profiles were investigated in the experimental stations of the Forest Research Institute: Gabra in the Lozen Mountain (grassland, deciduous and mixed forest plots); Govedartsi in the Rila Mountains (grassland, Scots pine, Norway spruce plots); Igralishte in the Maleshevska Mountain (grassland, deciduous – oak and Scots pine forest plots) situated in South-Western Bulgaria (Table 1). The studied soils were classified as Cambisols and the identified qualifiers were added on the second level according to WRB 2015 (IUSS Working group WRB 2015) (Kercheva et al. 2019).

Vertically-oriented cores were sampled from the surface (0–5 cm) and the subsurface (10–15 and 15–20 cm) soil layers in four replicates in 100 cm^3 metal cylinders to determine the soil bulk density (ρ_b, g/cm^3) and the soil water retention at suctions less than 33 kPa (ISO 11274:1998). The bulk density and the soil water content (W, g/g) of these undisturbed soil samples were determined by the gravimetric method after oven drying at 105 °C until a constant dry weight was achieved. The gravel (2–60 mm, FAO 2006) content was determined in each ring and was expressed as the volume percent.

The soil texture fractions were determined after chemical dispersion with sodium pyrophosphate ($Na_4P_2O_7$) and the preliminary removal of the organic matter from the soil sample with 30% hydrogen peroxide. The fractions of sand (2–0.063 mm), silt (0.063–0.002 mm) and clay (< 0.002 mm) were determined according to ISO 11277:2009 to apply the textural classification of IUSS Working Group WRB (2015). The particle density (ρ_s, g/cm^3) analysis was carried out in water with 100 cm^3 pycnometers. Consequently, the total porosity (*Pt*, %) was calculated using the measured ρ_b and ρ_s ($Pt = [(\rho_s - \rho_b)/\rho_s] \times 100$). The total soil organic carbon content (SOC, %) was determined by the modified Tjurin's method (Kononova 1966; Filcheva & Tsadilas 2002). The SOC content was classified according to Filcheva (Filcheva 2014). Data on the soil pH, the total soil nitrogen content and the cation exchange capacity were presented in Kercheva et al. (2019).

The wetting of the undisturbed soil samples at a suction of 0.25 kPa on a sand bath was chosen instead of full water saturation in order to avoid the possibility of destroying the soil structure by slaking, which can often occur with coarse textured soils. The soil water retention of the samples at suctions less than 33 kPa was determined in four replicates (100 cm^3 rings) with a suction type apparatus (Shot filters G5 with pore diameters of 1.0–1.6 μm). A negative matric pressure was applied by means of a hanging water column for the range from the matric potential (pF)

Table 1. Location of the soil profiles and basic properties

Soil variety	Land use	Depth (cm)	SOC (%)	pH (H_2O)	Sand	Silt (%)	Clay	Texture class
Gabra (23.63E; 42.53N; 916–937 m a.s.l.)								
Eutric Leptic Cambisols (Ochric)	grassland	0–5	1.5	5.2	32	47	21	loam
Dystric Cambisols	deciduous forest	0–5	2.7	3.9	52	29	20	sandy loam
		15–20	0.9	3.8	52	31	17	sandy loam
	mixed forest	0–5	1.5	4.0	54	32	14	sandy loam
Govedartsi (23.46–23.42E; 42.22N; 1503–1579 m a.s.l.)								
Dystric Cambisols (Humic)	grassland	0–5	5.9	4.1	46	34	20	loam
	Scots pine	0–5	4.2	4.2	43	37	19	loam
	Norway spruce	0–5	6.8	3.7	48	32	20	loam
Igralishte (23.13E; 41.57; 848–869 m a.s.l.)								
Eutric Leptic Cambisols (Ochric)	grassland	0–5	2.9	4.6	72	21	7	sandy loam
		10–20	0.4	4.1	82	15	3	loamy sand
Eutric Cambisols (Ochric)	deciduous forest	0–5	2.4	4.5	73	25	2	loamy sand
		10–15	1.1	3.9	74	21	5	loamy sand
	Scots pine	0–5	0.3	4.5	82	14	4	loamy sand

SOC – soil organic carbon content

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1 to pF 2.0 (pF = $\log_{10}(|-\text{cm } H_2O|)$) and by connecting to a vacuum chamber at pF 2.5. The soil water retention at suction 1 500 kPa (pF 4.2 – wilting point, WP) was determined in three replicates using a pressure membrane apparatus (ISO 11274:1998). The hygroscopic water content (pF 5.6) was determined using the vapour-pressure method with a controlled 75% relative air humidity in desiccators containing a saturated solution of NaCl. The Soil Water Retention Curve (SWRC) parameters of the van Genuchten equation estimated by Kercheva et al. (2019) were used to calculate the matric potentials at a water content between pF 2.5 and pF 4.2. In this study, we accept the water retention at pF 2.5 (potential –33kPa) as the field capacity (FC), as it is used in the pedotransfer functions and hydrological modelling (Rawls et al. 2003; Tóth et al. 2015). The volume of air-filled pores at a given suction P was calculated as the difference between the total soil porosity and the measured volume of the water content (θ) retained at this suction.

In the current study, direct measurements of the thermal properties of the studied soils were conducted with a KD2Pro reader-logger device and its two thermal sensors: SH-1 and TR-1. The SH-1 dual-needle sensor was used to measure λ, C_v and α in the laboratory conditions. The single needle TR-1 sensor was used to measure λ in the field conditions. Both are based on ASTM D5334. The KD2Pro device uses the transient line heat source method to take measurements.

The thermal properties were measured during drainage of the samples at each applied negative matric pressure on the suction type apparatus and, additionally, during the air-drying of the samples. The SH-1 sensor was placed in the centre of the metal cylinders and, after a 15 min interval to achieve equilibrium, the thermal properties were measured.

RESULTS AND DISCUSSION

The data for some basic soil characteristics are presented in Table 1. The Dystric Cambisols (Humic) in the Govedartsi station, which is situated at the highest altitude, was characterised with the finest texture (loam) and the highest soil organic carbon content (4.2–6.8%). The Cambisols in the Igralishte station had a sand content above 70% and a clay content below 10%, which was a precondition for structureless soil. The SOC in the Igralishte and Gabra stations varied in similar ranges from 0.3% to 2.9%, but the soil texture in the Gabra station was finer with a clay content between 14 and 21%. The climate conditions and land cover created a different degree of humus accumulation and, hence, influenced the soil water retention properties in these coarse textured soils (Kercheva et al. 2019). All the soils were with an acid reaction (Table 1).

The volumetric proportions of the solid, liquid and gas constituents are illustrated in Figure 1. It can be seen that the values of the total porosity (*Pt*) ranged from 50 to 63.4% in Gabra (Figure 1A); from 60.2 to 75.6% in Govedartsi (Figure 1B) and from 50.1 to 68.8% in Igralishte (Figure 1C). The water retained at pF 2.5 was less than half of the total porosity which indicated the dominance of the large pores in the porous continuum of the Cambisols. While the organic matter increased the *Pt*, the presence of the skeleton decreased it (Figure 2). These opposite effects are well described by the obtained multiple regression equation:

$$Pt = 64.0 + 2.04 \times \text{SOC} - 0.62 \times \text{skeleton}; \quad R^2\text{adj} = 0.748, \text{SEE} = 3.0\% \tag{1}$$

where:
skeleton – soil skeleton (coarse fragments > 2 mm);
SEE – standard error of estimate.

The thermal properties were measured at a water content corresponding to the applied matric potentials in the range from pF 0.4 to 2.5 and to the estimated potentials greater than pF 2.5 during the air-drying of the samples. The obtained data for the soil thermal properties can be expressed versus the fractions of water, solids and air (Ochsner et al. 2001; Kodešová et al. 2013) or of the matric suction (pF) (Lu et al. 2019). The relationships with the volumetric water content are illustrated with our dataset in Figures 3–5. The λ in the surface soil layers with a high SOC and *Pt* were smaller and varied less over the whole range of the water content than in the layers with a low SOC and *Pt* (Figures 3, 6). The finer texture of 0–5 cm under the grassland in Gabra caused a slight decrease in λ near saturation due to the soil swelling. The C_v was also lower in the humic horizons than in the mineral horizons, but with the same increasing slope (Figure 4). The low increase in λ for the humic horizons led to almost an absence of the dependence between α and the water content (Figure 5), while, for the mineral horizons, the relationship was positive. The data

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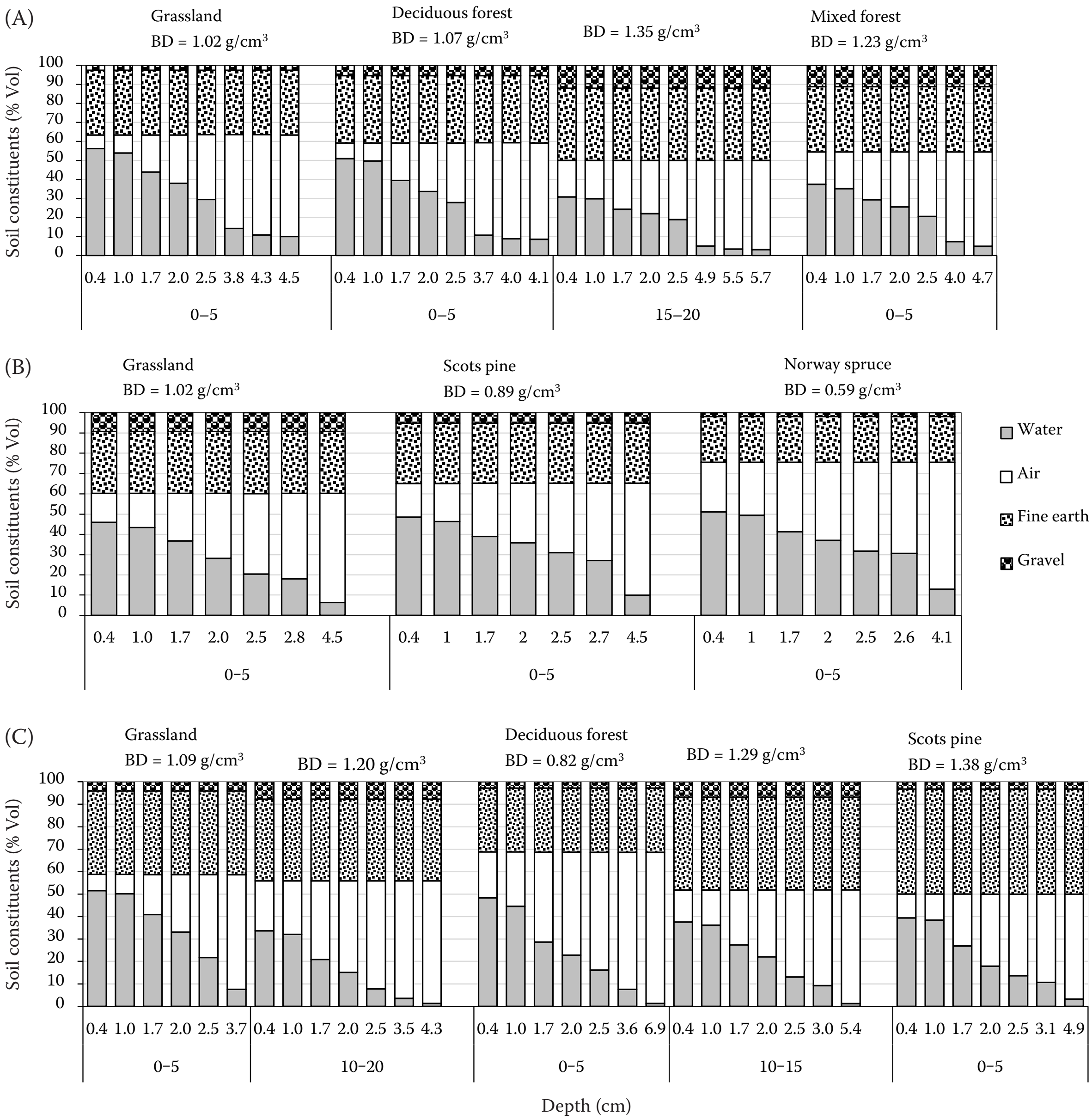

Figure 1. Volumetric percentage of solids (fine earth, gravel) and pores filled with water and air at different matric potentials pF (pF = $\log_{10}(|-\text{cm } H_2O|)$) for Cambisols in Gabra (A), Govedartsi (B) and Igralishte (C)

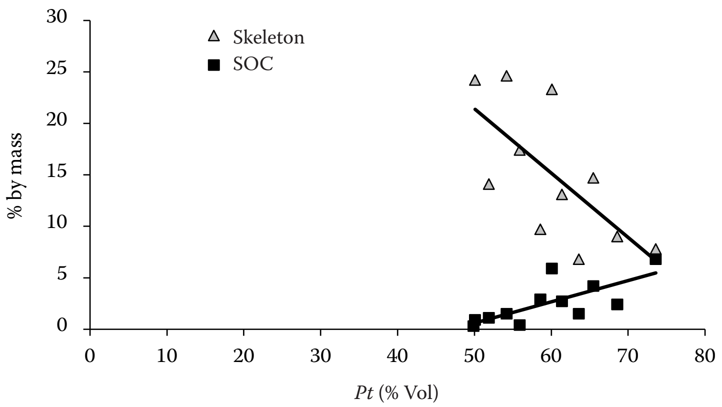

Figure 2. The soil organic carbon content (SOC) and soil skeleton content (coarse fragments > 2 mm) versus the total porosity (*Pt*)

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for some of the physical characteristics and the soil thermal conductivity measured in the field (TR-1 sensor) and laboratory (SH-1 sensor) conditions are presented in Table 2. The reduction in λ in the surface horizons with a high SOC were confirmed by the measured values in the field conditions.

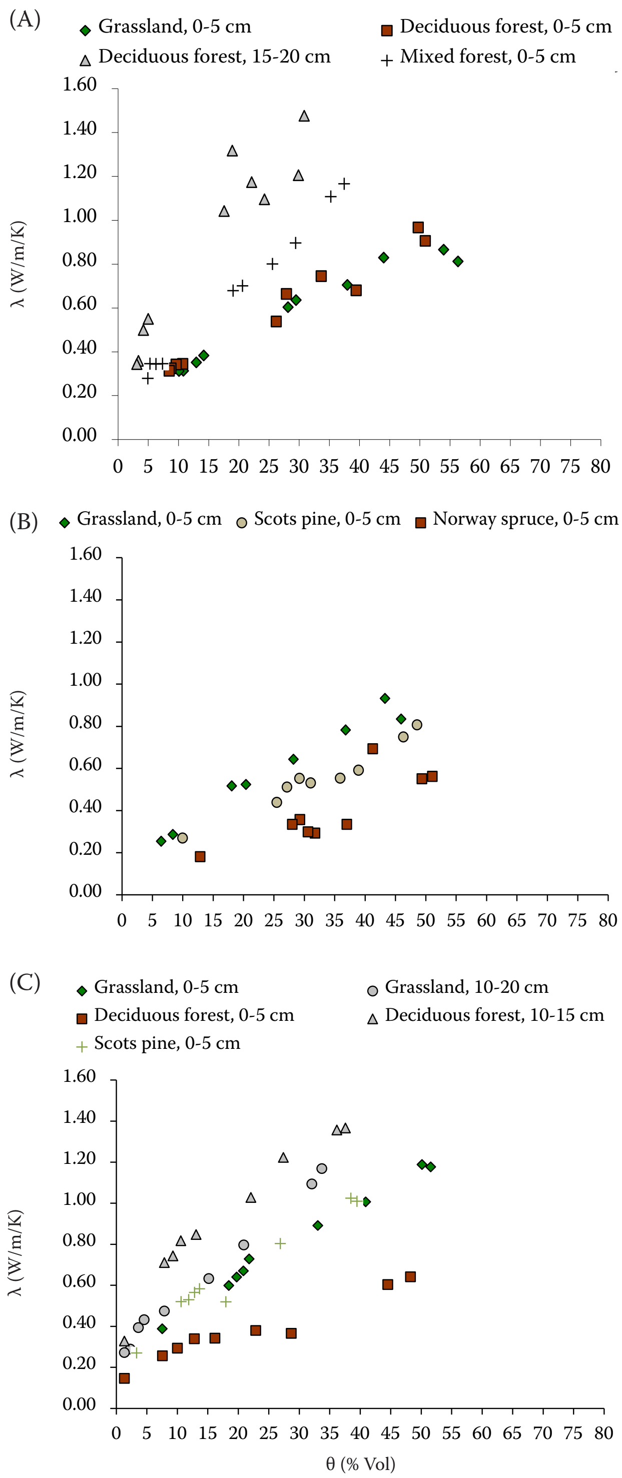

Figure 3. Measured thermal conductivity (λ) as a function of the soil water content (θ) under different land use in Gabra (A), Govedartsi (B) and Igralishte (C)

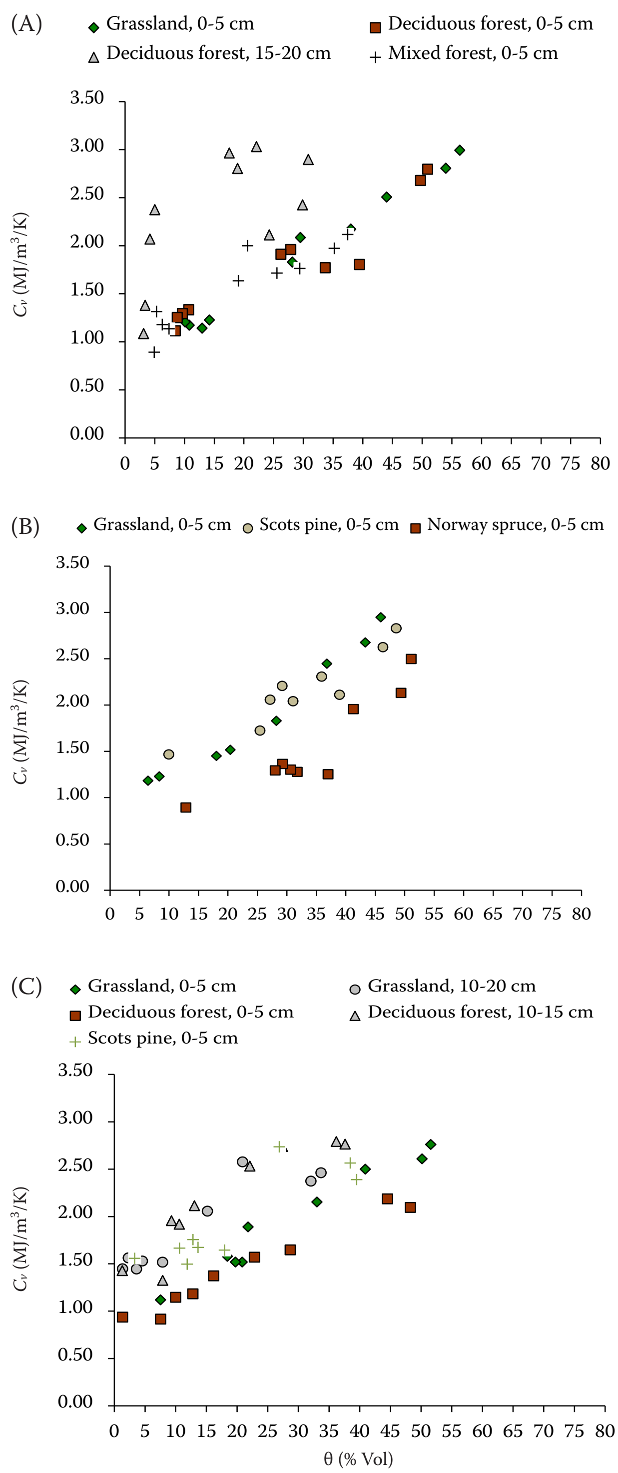

Figure 4. Measured volumetric heat capacity (C_v) as a function of the soil water content (θ) under different land use in Gabra (A), Govedartsi (B) and Igralishte (C)

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The lowest values in the total porosity (*Pt* = 50%) and aeration pores (AP = 31%) at pF = 2.5 (FC) at depth 15–20 cm under the deciduous forest (Gabra) led to the highest observed λ (1.32 W/m/K), C_v (2.80 MJ per m^3/K) and α (0.47 mm^2/s) values (Table 2). The maximum value of the thermal conductivity can be explained with the higher λ values of the solid particles (λ = 3 – 8.8 W/m/K) in comparison with those of water (λ = 0.57 W/m/K), air (λ = 0.025 W/m/K) and organic matter (λ = 0.25 W/m/K) (de Vries 1963). The ratios of θ to AP for the Dystric Cambisols (15–20 cm) under the deciduous forest (Gabra) were as follows: close to saturation ~1.6, at FC ~0.6 and close to the air-dry conditions ~0.1. In the field conditions, the measured value of λ (TR-1 sensor) was also the highest (λ =1.36 W/m/K) in comparison with all the studied variants. The greater scattering of λ and *Cv* in this case can be explained with the non-homogeneity of the sample which influenced the readings at different potentials (the sensor was inserted before the reading and then the sample was taken out after the reading). Nevertheless, the thermal diffusivity, in this case, showed the same dependency on the soil water content as the surface 0–5 cm soil layer under the mixed forest, having similar soil properties (skeleton 22–24%, SOC 0.9–1.5%).

A contrasting case was the Dystric Cambisols (Humic) under the Norway spruce forest in Govedartsi which had the highest SOC content (6.8%) (Table 1), the highest *Pt* value (75.6% vol.) and the lowest ρ_b value (0.59 g/cm^3) (Figure 1B). These SOC, *Pt* and ρ_b values led to the lower values in the thermal properties (λ = 0.29 W/m/K, C_v = 1.28 MJ/m^3/K and α = 0.23 mm^2/s) measured in the laboratory conditions at pF = 2.5 ($\theta_{pF2.5}$~32%). In conditions close to saturation, the ratio θ:AP was 2.1, it was 0.7 at FC and it was 0.2 at the air-dry conditions. The AP content (~44%) at the FC conditions was greater than the other variants in Govedartsi (Table 2). For the variants under the grassland and under the Scots pine, the decreasing Pt and AP values yielded higher λ, C_v and α values compared to the variant under the Norway spruce forest at the FC and conditions close to saturation.

The lowest SOC (0.3%) and *Pt* (50% vol.) values and the highest ρ_b value (1.38 g/cm^3) were determined for the Eutric Cambisols (Ochric) under the Scots pine forest (0–5 cm) in Igralishte. At pF = 2.5, $\theta_{pF2.5}$~14% and AP~36%, the soil thermal properties were λ = 0.58 W/m/K, C_v = 1.67 MJ/m^3/K and α = 0.35 mm^2/s (Table 2). For that variant at pF = 0.4, the ratio θ : AP was ~3.7, it was ~0.4 at FC and ~0.1 at close to air-dry conditions. For the Eutric Cambisols (Ochric) (0–5 cm) under the deciduous forest in Igralishte,

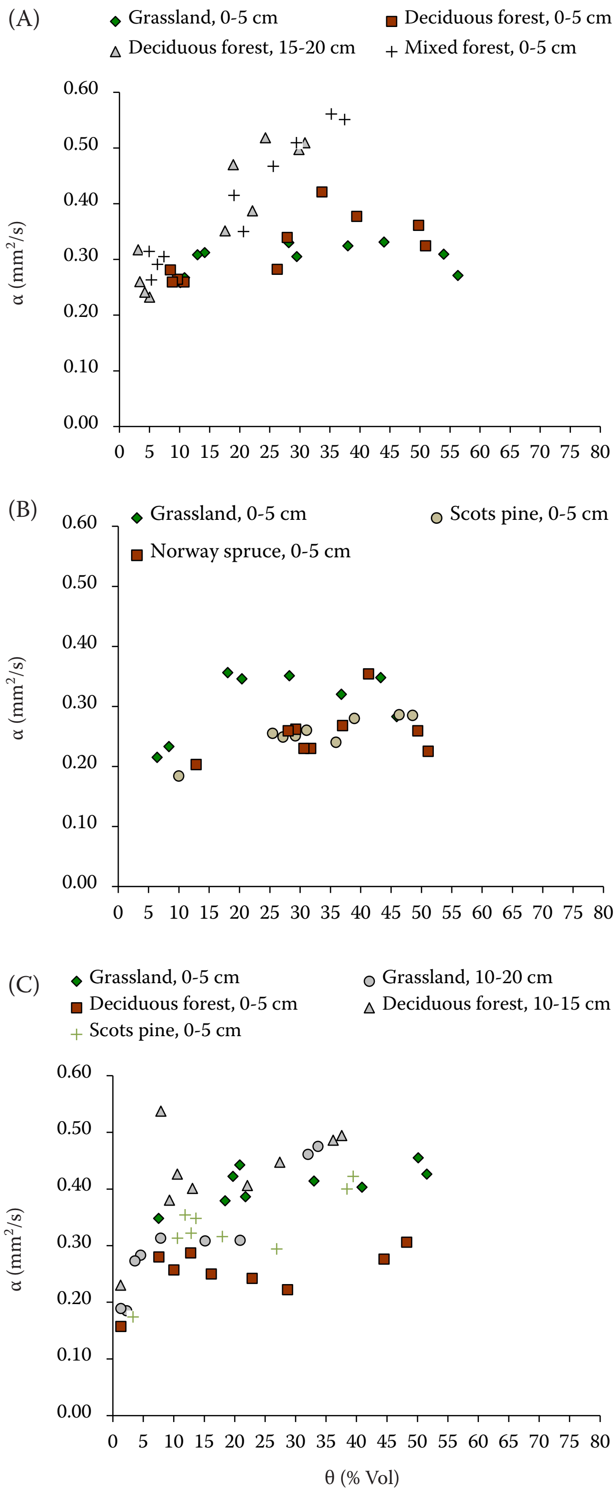

Figure 5. Measured thermal diffusivity (α) as a function of the soil water content (θ) under different land use in Gabra (A), Govedartsi (B) and Igralishte (C)

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Table 2. Measured values of the soil thermal conductivity (λ, W/m/K) for the studied soil varieties in the field (TR-1 sensor) and laboratory (SH-1 sensor) conditions

Land use	Depth (cm)	Field (TR-1)				Laboratory (SH-1)										
		ρ_b	θ	AP	λ	ρ_b	pF_d	θ_d	AP_d	λ_d	$\theta_{pF2.5}$	$AP_{pF2.5}$	$\lambda_{pF2.5}$	$\theta_{pF0.4}$	$AP_{pF0.4}$	$\lambda_{pF0.4}$
Gabra																
Grassland	0–5	1.08	24.3	37.3	0.67	1.02	4.5	10.1	53.3	0.31	29.5	34.0	0.64	56.3	7.1	0.81
Deciduous forest	0–5	1.02	25.7	35.9	0.77	1.07	4.1	8.5	50.8	0.31	27.9	31.4	0.66	50.9	8.4	0.91
	15–20	1.38	22.2	26.8	1.36	1.35	5.7	3.1	46.9	0.34	18.9	31.1	1.32	30.8	19.1	1.48
Mixed forest	0–5	1.26	15.4	38.0	0.99	1.23	4.7	4.9	49.6	0.28	20.6	33.9	0.70	37.5	17.1	1.17
Govedartsi																
Grassland	0–5	1.07	26.5	31.8	0.84	1.02	4.5	6.4	53.8	0.26	20.4	39.8	0.52	45.9	14.3	0.83
Scots pine	0–5	0.87	29.8	36.6	0.58	0.89	4.5	10.0	55.3	0.27	31.0	34.2	0.53	48.5	16.7	0.81
Norway spruce	0–5	0.60	32.9	42.2	0.52	0.59	4.1	12.9	62.7	0.18	31.8	43.9	0.29	51.1	24.5	0.56
Igralishte																
Grassland	0–5	1.08	13.6	45.3	0.66	1.09	3.7	7.5	51.2	0.39	21.8	36.9	0.73	51.6	7.2	1.18
	10–20	1.33	9.7	41.7	0.91	1.20	4.3	1.3	54.6	0.27	7.9	48.0	0.48	33.7	22.1	1.17
Deciduous forest	0–5	0.83	14.6	53.6	0.12	0.82	6.9	1.3	67.4	0.15	16.2	52.5	0.34	48.3	20.6	0.64
	10–15	1.28	11.3	41.0	0.84	1.29	5.4	1.3	50.6	0.33	13.1	38.8	0.85	37.6	14.2	1.37
Scots pine	0–5	1.38	15.7	34.2	0.53	1.38	4.9	3.3	46.7	0.27	13.6	36.3	0.58	39.5	10.6	1.01

ρ_b – bulk density (g/cm^3); θ – volumetric water content (% Vol); AP – air filled pores (% Vol); pF – matric potential; d – air-dry conditions

the highest *Pt* (~69% v/v) and AP values, and the lowest ρ_b value (0.82 g/cm^3) determined the lower thermal properties compared with the grassland and Scots pine forest land use at the FC conditions. The changes in λ within the studied wetness range were lower compared to the other soil layers with similar properties (e.g., 10–15 cm under the deciduous forest in Gabra). This can be explained by the absence of this soil structure, the low skeleton content and the high sand particle content (82%) with a small surface area.

The effect of increasing ρ_b with the depth on the soil thermal properties was examined for the studied soils with the different texture: sandy loam of the Dystric Cambisols in Gabra and loamy sand of the Eutric Cambisols (Ochric) in Igralishte, both under a deciduous forest. The ρ_b increased with the depth by 21% and 36% in Gabra and Igralishte, respectively. The rise in the thermal properties was by 50% and 60% for λ, by 30% and 35% for C_v, by 28% and 38% for *α*, respectively, for the sandy loam soil and the loamy sand soil. The results correspond to those obtained by Abu-Hamdeh and Reeder (2000) where the high ρ_b enlarged the contact area between the soil particles and caused an increase in λ. In our study, the largest increase was observed for λ (Figure 6) in comparison with C_v and α. This is in accordance with Hillel (1980) who pointed out that the change in λ is larger than the change in C_v which is a consequence of the λ dependence on the volume

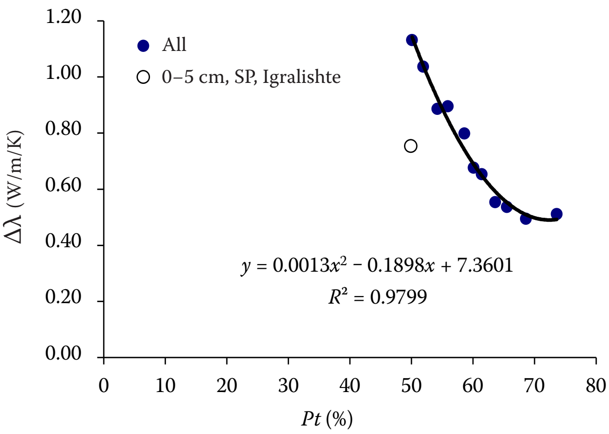

Figure 6. Variation (max-min) of the thermal conductivity (Δλ) observed over the whole range of wetness versus the total porosity (*Pt*)

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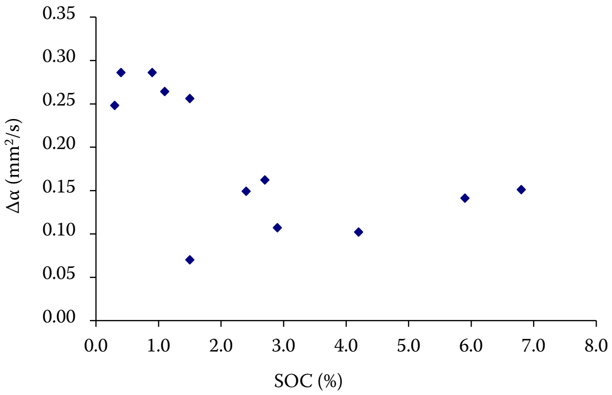

Figure 7. Variation (max-min) of the thermal diffusivity ($\Delta\alpha$) observed over the whole range of wetness versus the soil organic carbon content (SOC)

composition and also on the size, the shape and the spatial arrangements of the soil particles. Additionally, the results obtained for the Eutric Cambisols (Ochric) agree with the statement of Usowicz (1993) and Tong et al.(2020) that for a given θ, a larger ρ_b always results in larger values for each of the soil thermal properties. At conditions close to air-dry with a lower water content, this effect of ρ_b was more pronounced.

The direct and indirect influence of SOC on the soil thermal properties was best pronounced by the dependence of the variation in the thermal diffusivity ($\Delta\alpha$) over the whole range of wetness on the SOC (Figure 7). It can be concluded that, in horizons with a SOC of less than 1.5%, the variation of α with θ was $\Delta\alpha = 0.235 \pm 0.082$ mm^2/s and was 1.7 times higher than in the horizons with a higher SOC, where $\Delta\alpha = 0.135 \pm 0.025$ mm^2/s.

CONCLUSION

The thermal properties of Cambisols under different land use in mountain regions were determined at the retained water contents at the applied matric suctions on the undisturbed soil samples. The soil organic carbon content affected the obtained information through its thermal properties and through its influence on the soil structure, especially in the soils with the high organic content. The lowest value of the thermal conductivity was established in the surface Dystric Cambisol (Humic) horizons in the experimental station Govedartsi (Rila Mountain) because of the high porosity and the high organic carbon content. The soil thermal conductivity increased with the depth under the deciduous forest (Gabra and Igralishte) due to the lower organic carbon content and total porosity. There were no such changes in subsurface horizon under the grassed associations.

In the horizons with a SOC less than 1.5%, the variation in the thermal diffusivity over the whole range of wetness was 1.7 times higher than those with the higher SOC. This information can be used for the estimation of the soil heat flux and the prediction of soil temperature distributions.

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