



Soil thermal properties of forest biogeocenoses in steppe zone as a diagnostic indicator of their soil genesis

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Soil is a specific natural body, which is characterized by a number of features due to which it differs from living organisms and rocks. One of these features is its thermal properties. The most important thermal properties of the soil are thermal conductivity, thermal capacity and thermal diffusivity, which reflect the specific features of the set of properties inherent in different soils. As a result of the studies, the existence of a direct relationship between the values of thermal conductivity and thermal diffusivity of Calcic Chernozem and the content of the silt fraction in them, as well as between the thermal capacity and the content of organic matter in them. The established relations do not appear clearly in Luvic Chernozem and Chernic Phaeozem. The maximum thermal properties for Luvic Chernozem and Chernic Phaeozem were found in the eluvial horizon, which in the lower part borders on the illuvial horizon. The eluvial horizons of Luvic Chernozem and Chernic Phaeozem are characterized by lower thermal properties compared with the illuvial horizons. The thermal properties of soils can be used to clarify the distribution characteristics of the silt fraction and organic matter along the profile, as well as determination of the intensity of eluvial-illuvial processes. The establishment of these soil features is an important characteristic of their soil genesis, which is especially important for chernozem soils under forest vegetation.

Keywords: thermal conductivity; thermal capacity; thermal diffusivity; silt content; organic matter content; eluvial-illuvial processes

Introduction

The thermal properties of the soil are its important characteristic, which determines the accumulation and movement of heat in the soil, and also affects the temperature and heat flux in the soil depending on time and depth (Abu-Hamdeh, 2003). The heat flux distribution in soil subject to a temperature gradient is based on three main thermal properties of the soil: thermal conductivity (λ), thermal capacity (C) and thermal diffusivity ($\alpha = \lambda / C$). Changes in temperature affect the physical properties of the soil, causing its thermal properties changes (Boukelia et al., 2019).

Among the thermal properties of the soil, the most important are thermal conductivity and thermal capacity. As it has been shown in investigations (Abu-Hamdeh, Reeder, 2000), the thermal conductivity of the soil is associated with its microclimate. It was found that thermal conductivity increases with increasing soil density and moisture content. An increasing of amount of added salts and the percentage of organic matter in the soil decreases the thermal conductivity. In general, sandy soils are characterized by higher thermal conductivity compared to clay loam. The research results of Vidana Gamage et al. (2019) indicate that the thermal properties of the soil are more dependent on the moisture content in it than on the content of organic matter and structural-aggregate composition. Other scientists cite data that

the thermal properties of the soil are mainly determined by the total content of organic matter, and not by its structural-aggregate composition, bulk density and moisture (Zhu et al., 2019).

Considering the presented data, it can be assumed that the thermal properties of the soil can be used to evaluate some of its physical and chemical properties, which determine the characteristics of the genesis of each individual soil.

Based on this, the goal of our work is to study the thermal properties of soils with their subsequent use to interpret the features of soil genesis in forest biogeocenoses of the steppe zone.

Materials and methods

The investigation of the thermal properties of soils of forest biogeocenoses was carried out using soil samples taken from five soil sections laid in five trial plots in the Glubokiy ravine.

A detailed description of the trial plots and soil sections is given in the work of V. M. Yakovenko (2014). Below we give a brief description of the studied objects using the above work.

Trial plot 1 is located on the virgin steppe, located on the northern exposition of the ravine. The area has a slope of 8° northern exposure. *Poa angustifolia* L., *Elytrigia repens* (L.) Nevski, *Achillea millefolium* L., *Salvia nemorosa* L., *Artemisia absinthium* L., *Euphorbia vibrata* Waldst et Kit., *Galium aparine* L., *Vilola odoratata* L., *Lathyrus tuberosus* L.,

Convolvus arvensis L. are present in the grassy cover. Soil – Calcic Chernozem (Siltic, Tonguic).

Trial plot 2 is located on the middle third of the slope of the northern exposition of the ravine. The area has a slope of 15° northern expositions. In the tree layer there are *Tilia cordata* Mill., *Fraxinus excelsior* L., *Acer platanoides* L., *Acer campestre* L., *Ulmus minor* Mill. The grassy cover is formed by *Glacoma hederacea* L., *Stellaria holostea* L., *Chelidonium majus* L., *Poa nemoralis* L., *Galium aparine* L., *Vilola odorata* L. Soil – Luvic Chernozem (Siltic, Hyperhumic, Pachic).

Trial plot 3 is located on a leveled area of the ravine. In the tree layer *Fraxinus excelsior* L., *Acer campestre* L., *Ulmus minor* Mill., *Acer platanoides* L., *Quercus robur* L., *Tilia cordata* Mill. The grass cover is formed by *Stellaria holostea* L., *Chelidonium majus* L., *Galium aparine* L., *Anthriscus sylvestris* (L.) Hoffm., *Aegopodium podagraria* L., *Geum urbanum* L., *Asarum europaeum* L., *Urtica dioica* L., *Alliaria petiolata* (M. Bied.) Cavara et Grande). Soil – Chernic Phaeozem (Siltic, Pantocolluvic, Hyperhumic, Pachic).

Trial plot 4 is located on the middle third of the southern exposition of the ravine. The area has a slope of 14° southern exposure. In the tree layer are *Fraxinus excelsior* L., *Acer campestre* L., *Ulmus minor* Mill., *Tilia cordata* Mill., *Acer platanoides* L. The grassy cover is formed by *Glomerulus hederacea* L., *Viola odorata* L., *Chelidonium majus* L., *Galium aparine* L., *Anthriscus sylvestris* (L.) Hoffm., *Geum urbanum* L., *Asarum europaeum* L., *Trifolium medium* L., *Aristolochia clematidis* L., *Potentilla argentea* L. Soil – Luvic Chernozem (Siltic, Hyperhumic, Pachic).

Trial plot 5 is located on the virgin steppe, located on the southern exposition of the ravine. The area has a slope of 3° southern exposure. Grass cover formed by *Festuca valesiaca* Goud. s.l., *Poa angustifolia* L., *Elytrigia repens* (L.) Nevski, *Poa nemoralis* L., *Lathyrus tuberosus* L., *Achillea millefolium* L., *Euphorbia vigrata* Waldst. et Kit., *Thymus marschallianus* Willd., *Linum hirsutum* L., *Agrimonia eupatoria* L., *Medicago romanica* Prod., *Melica transsilvanica* Schur, *Salvia nemorosa* L. Soil – Calcic Chernozem (Siltic, Tonguic).

The air temperature was measured using a Starmeter digital anemometer-thermometer-hygrometer (ST8021). The temperature of the soil (at the surface (0 cm) and at depths of 5, 10, 15, 20, 25, 30, 35, 40 and 50 cm) was determined using a set of temperature sensors. Ten sensors were placed in a pre-prepared well with a depth of about 52 cm. Using the application developed by A. A. Gorban, temperature sensors connected via Bluetooth to a smartphone, transmitting digital information to it regarding the measured soil temperature. The thermal properties of the soil (thermal diffusivity, thermal capacity and thermal conductivity) were determined by the method of pulsed heating, which is the most used in such investigations (Abu-Hamdeh, Reeder, 2000; Bachmann et al., 2001). Investigations were performed using the installation and software described in the work (Gorban V., Gorban A., 2007).

Results and discussion

Field measurements of soil temperature (layer 0–50 cm) in the summer period of 2018 gave possibility to obtain the results, which are presented in Fig. 1. As a result of an additional measurement of air temperature, the indicators that are presented in Table 1 were obtained and calculated. An analysis of these data showed that the highest air temperature is typical for the trial plot 1, which is located on the northern edge of the ravine. The air temperature, which was measured on the trial plot 2 (the southern edge of the ravine), turned out to be 2 degrees lower than on the trial plot 1. When transitioned under the forest stand, the air temperature decreases by an average of 1.5 degrees (trial plots 2 and 4) and at the lowest point of the ravine (trial plot 3 in the leveled area of the ravine), the lowest air temperature is observed compared to other trial areas, with a minimum difference of 2 degrees and a maximum of about 6 degrees.

The maximum temperature of the soil surface was found on the trial plot 5. Transition under the canopy of forest vegetation on the trial plot 4 led to a decrease in temperature by more than 4 degrees. The transition from trial plot 1 to trial plot 2 led to a decrease in soil surface temperature by 2,4 degrees. The minimum temperature of the soil surface, as well as the air temperature, was found on the trial plot 3. Moreover, the maximum temperature difference was about 8 degrees (trial plots 3 and 5).

Table 1

Temperature indicators of air and studied soils (06 August 2018)

Trial plot 1 – Calcic Chernozem	Trial plot 2 – Luvic Chernozem	Trial plot 3 – Chernic Phaeozem	Trial plot 4 – Luvic Chernozem	Trial plot 5 – Calcic Chernozem
Air temperature, °C				
32,3	30,9	26,6	28,6	30,3
Soil surface temperature, °C				
30,1	27,7	26,5	30,3	34,6
Soil temperature at a depth of 50 cm, °C				
23,1	21,5	20,1	25,1	25,8
The average temperature of the soil layer is 0–50 cm, °C				
25,5	24,2	23,0	27,9	29,8
The difference between air temperature and average soil temperature				
6,8	6,7	3,6	0,7	0,5
The difference between the surface temperature of the soil and at a depth of 50 cm				
7,0	6,2	6,4	5,2	8,8

The maximum soil temperature at a depth of 50 cm was also identified in the trial plot 5. The transition under the canopy of forest vegetation reduces the recorded temperature by less than 1 degree. The difference between soil temperatures at a depth of 50 cm of trial plots 1 and 2 is about 1,5 degrees. The minimum soil temperature at a depth of 50 cm was detected in the trial plot 3. The maximum difference between this characteristic was found for trial plots 3 and 5 and is almost 6 degrees.

The calculation of the average temperature of the soil layer of 0–50 cm revealed that its maximum value is also characteristic of the trial plot 5. When transitioning to trial plot 4, the average value decreases by almost 2 degrees. When moving from trial plot 1 to trial plot 2, the average temperature decreases slightly more than 1 degree, as well as when transitioning from trial plot 2 to trial plot 3. The maximum difference in average temperature of trial plot 3 and 5 is almost 7 degrees.

The maximum difference between the air temperature and the average soil temperature was found on the trial plot 1 and its gradual decrease is observed towards the trial plot 5.

Calculations of the difference between the surface temperature of the soil and at a depth of 50 cm showed that its maximum value is typical for trial plot 5, slightly less for trial plot 1. Transition under the canopy of forest vegetation helps to reduce the observed temperature difference, and on trial plot 3 in thalweg observed its increase (Table 1). This indicator is important for understanding the thermal properties of the upper horizons of the investigated soils, since it makes it possible to indirectly judge their thermal conductivity, thermal capacity, and thermal diffusivity. Considering the obtained data, it can be assumed that the soils of the trial plots 1 and 5, which differ in the increased temperature difference of the soil surface and at a depth of 50 cm, are characterized by increased values of thermal capacity and relatively small values of thermal conductivity and thermal diffusivity. The soil of the test area 4 should have a small thermal capacity and increased values of thermal conductivity and thermal diffusivity. The soils of the

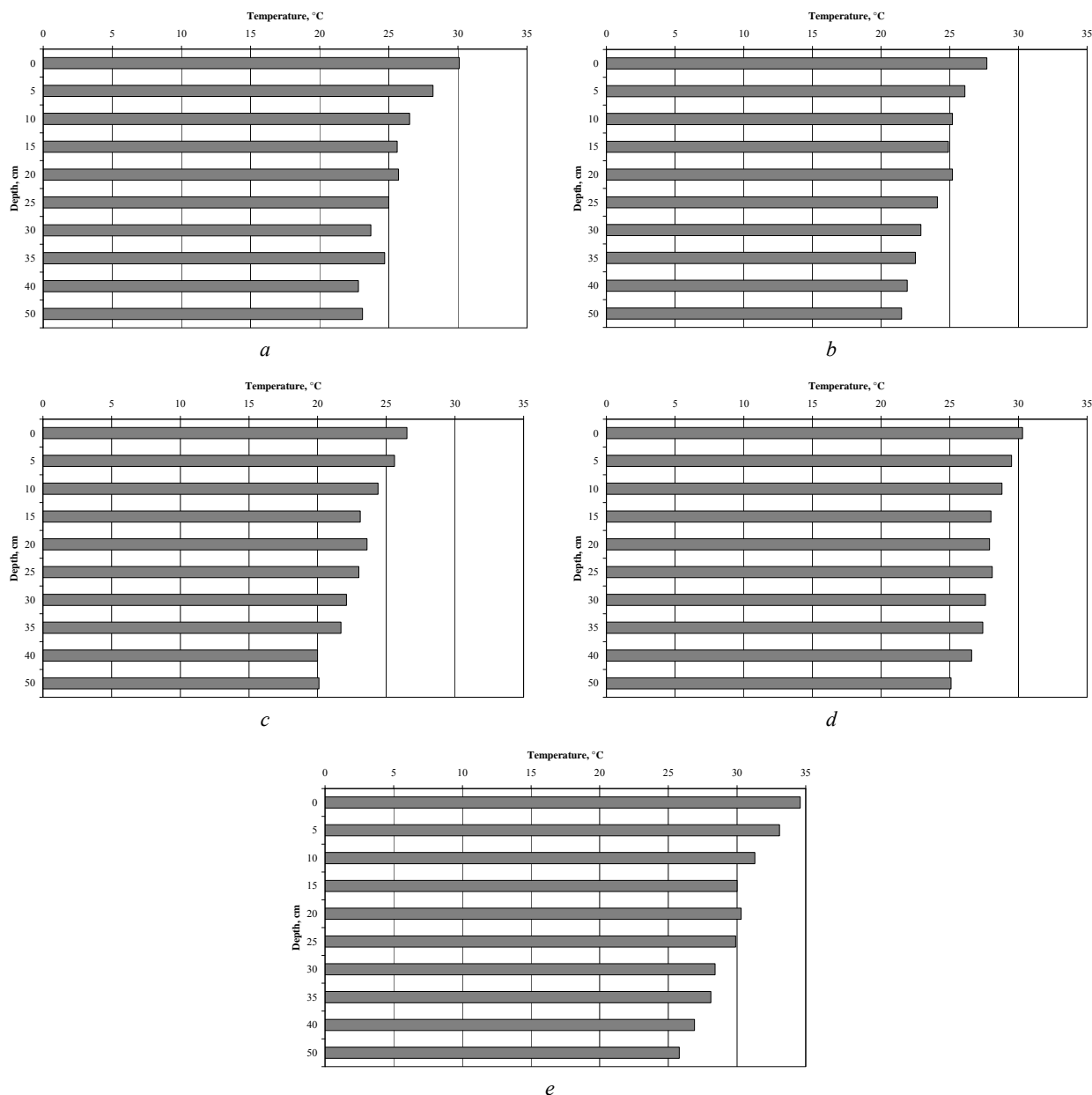


Fig. 1. Temperature indicators of the studied soils at a depth from 0 to 50 cm: a – trial plot 1; b – trial plot 2; c – trial plot 3; d – trial plot 4; e – trial plot 5

trial plots 2 and 3 should naturally be characterized by relatively average thermal properties.

To verify the formulated assumptions, we determined the thermal properties of the investigated soils, the results of which are presented in Table 2.

As a result of the investigation of the thermal properties of the soil of trial plot 1, it was found that the maximum thermal conductivity ($0.775 \text{ J}/(\text{m}\cdot\text{s}\cdot\text{K})$) is characteristic of the Hpk horizon, while other values show lower values of this characteristic. The maximum thermal capacity ($1.335 \text{ MJ}/(\text{m}^3\cdot\text{K})$) was also found in the Hpk horizon, and its value decrease is observed with increasing of depth. The maximum value of thermal diffusivity ($6.156 \times 10^{-7} \text{ m}^2/\text{s}$) was revealed in the Pk horizon; in general, along the profile with its depth, its gradual increase is observed. In general, the upper horizons are characterized by lower values of thermal conductivity and thermal capacity in comparison with the lower ones, while the upper horizons are characterized by higher values of thermal capacity. This is explained by the existence of a direct relationship between the thermal capacity and the content of organic matter (Teorii., 2007), the maximum values of which are associated with the upper horizons of chernozems (Belova, Travleyev, 1999; Degtyarev, 2011). The values of thermal

conductivity and thermal diffusivity turn out to be more dependent on the content of the silt fraction (Lukyashchenko, Arkhangelskaya, 2018), the increased content of which is characteristic of the lower horizons of ordinary chernozems (Medvedev, Laktionova, 2011). These relationships are most pronounced in zonal chernozems beneath the steppe vegetation, in which there are no significant differences in the distribution of the silt fraction over the upper and lower horizons (Travleyev, Belova, 2008). However, in soils with the intensity of eluvial-illuvial processes increases significantly, the revealed patterns are less pronounced.

When investigating the soils of the trial plot 2, it turned out that the maximum thermal properties ($0.727 \text{ J}/(\text{m}\cdot\text{s}\cdot\text{K})$, $1.292 \text{ MJ}/(\text{m}^3\cdot\text{K})$ and $5.675 \times 10^{-7} \text{ m}^2/\text{s}$) are associated with the eluvial horizon H4el, bordering at the bottom with the first illuvial horizon Hpil. It is precisely as a result of the leaching process that a silt fraction accumulates in this horizon, which leads to increased values of thermal properties in this horizon. In general, eluvial horizons naturally differ in smaller values of thermal properties as a result of leaching of the silt fraction in comparison with illuvial horizons.

The results of the study of the soil of trial plot 3 showed that in the eluvial horizon H3el, bordering in the lower part

Table 2
Thermal properties of the studied soils

Horizon	Depth, cm	Thermal conductivity, J/(m·s·K)	Thermal capacity, MJ/(m ³ ·K)	Thermal conductivity, 10 ⁻⁷ m ² /s
Trial plot 1 – Calcic Chernozem				
Hdk	0–8	0,717±0,028	1,297±0,034	5,665±0,357
Hk	8–23	0,719±0,033	1,279±0,068	5,761±0,333
Hpk	23–51	0,775±0,023	1,335±0,031	5,911±0,169
Phk	51–80	0,713±0,044	1,251±0,025	5,767±0,269
Pk	80–120	0,728±0,019	1,212±0,047	6,156±0,433
Trial plot 2 – Luvic Chernozem				
H1el	0–12	0,620±0,016	1,222±0,022	5,110±0,237
H2el	12–33	0,607±0,021	1,175±0,018	5,159±0,090
H3el	33–67	0,680±0,027	1,244±0,046	5,450±0,035
H4el	67–96	0,727±0,046	1,292±0,062	5,675±0,421
Hpil	96–140	0,682±0,030	1,277±0,029	5,361±0,150
Phil	140–166	0,696±0,070	1,280±0,029	5,471±0,656
Pilk	166–230	0,695±0,046	1,283±0,046	5,424±0,336
Trial plot 3 – Chernic Phaeozem				
H1el	0–8	0,698±0,029	1,282±0,038	5,506±0,101
H2el	8–34	0,671±0,028	1,276±0,027	5,308±0,186
H3el	34–60	0,741±0,021	1,300±0,012	5,797±0,211
Hil	60–118	0,716±0,014	1,325±0,021	5,534±0,146
Hpil	118–132	0,700±0,051	1,319±0,079	5,379±0,312
Phil	132–166	0,741±0,022	1,375±0,067	5,395±0,149
Trial plot 4 – Luvic Chernozem				
H1el	0–9	0,691±0,027	1,343±0,062	5,268±0,171
H2el	9–46	0,717±0,037	1,339±0,008	5,467±0,283
H3el	46–88	0,783±0,007	1,315±0,075	6,142±0,343
Hil	88–138	0,766±0,044	1,393±0,115	5,588±0,203
Hpil	138–160	0,782±0,007	1,400±0,090	5,790±0,417
Philk	160–187	0,749±0,028	1,380±0,116	5,560±0,425
Pilk	187–230	0,733±0,026	1,368±0,056	5,458±0,338
Trial plot 5 – Calcic Chernozem				
Hdk	0–6	0,711±0,012	1,243±0,022	5,799±0,128
Hpk	6–27	0,781±0,017	1,270±0,023	6,216±0,226
Phk	27–40	0,778±0,022	1,228±0,020	6,465±0,118
Pk	40–120	0,785±0,021	1,231±0,038	6,489±0,218

with the illuvial horizon Hpil, is the maximum values of thermal conductivity (0.741 J/(m·s·K)) and thermal diffusivity (5.797×10^{-7} m²/s). The maximum thermal capacity (1.375 MJ/(m³·K)) was found in the Phil horizon. The features of such a distribution of the thermal properties of this soil are also explained by the significant intensification of eluvial-illuvial processes.

Investigations of the thermal properties of the soil of trial plot 4 also revealed their dependence on the distribution characteristics of the silt fraction along the horizon. The maximum values of thermal conductivity (0.783 J/(m·s·K)) and thermal diffusivity (6.142×10^{-7} m²/s) were found in the eluvial horizon H3el, bordering in the lower part with the illuvial horizon Hil. The maximum thermal capacity (1,400 MJ/(m³·K)) is characteristic of the Hpil horizon. In general, there is an increase in the thermal capacity in the lower illuvial horizons compared to the upper eluvial horizons.

As a result of studying the soil of trial plot 5, it was found that the maximum values of thermal conductivity and thermal diffusivity (0.785 J/(m·s·K) and 6.489×10^{-7} m²/s, respectively) were found in the Pk horizon. In general, there is an increase in the values of the mentioned characteristics with depth. The maximum thermal capacities (1.270 and 1.243 MJ/(m³·K)) are characteristic of the upper Hpk and Hdk horizons, respectively, it indicates the maximum accumulation of organic matter in these horizons.

As a result of a direct determination of the thermal properties of the investigated soils, it was found the most assumptions were based on measuring air and soil temperatures are not confirmed.

Conclusion

Calcic Chernozem is characterized by increased values of the investigated temperature indices in comparison with Luvic Chernozem. The minimum values of these characteristics are established for Chernic Phaeozem. A direct relationship was established between the values of thermal conductivity and thermal diffusivity of Calcic Chernozem and the content of silt fraction in it. A direct relationship was found between the thermal capacity of Calcic Chernozem and the content of organic matter in it. The established relationships do not appear clearly in Luvic Chernozem and Chernic Phaeozem. The maximum values of thermal properties for Luvic Chernozem and for Chernic Phaeozem were found in the eluvial horizon, bordering in the lower part with the illuvial horizon. The eluvial horizons of Luvic Chernozem and Chernic Phaeozem are characterized by lower thermal properties compared with the illuvial horizons. The thermal properties of soils can be used to clarify the distribution characteristics of the silt fraction and organic matter along the profile, as well as to determine the intensity of the eluvial-illuvial processes. The establishment of these soil features is an important characteristic of their soil genesis, it is especially important for chernozem soils under forest vegetation.

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