Thermophysical Properties of Chernozem Soils Growing Ornamental Plants in Summer

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Abstract. Currently, there is no data on the transfer of heat and moisture of arboretum soils that grow such ornamental plants as Meyer lilac (Syringa meyeri), rowan “Alaya” (Sorbus aucuparia), and dwarf thuja “Danica” (Thuja occidentalis). We experimentally determined that the thermophysical qualities of chernozems in lilac plantations changed with the water regime in the growing season. The sample maximum values of volumetric heat capacity and thermal conductivity were observed in the dense illuvial horizon. The sample minimums were registered in the AB transition horizon. Thermal diffusivity was the highest at the lowest humidity. In rowan plantations, the moisture content in transitional and illuvial horizons AB and B changed insignificantly. Such moisture distribution corresponds to the slope aspect and the features of rowan. The thermophysical coefficients also slightly fluctuated in rowan plantations, especially in the underlying horizons AB and B. The same horizons displayed the sample maximum of thermal diffusivity. It corresponded to the moisture content of capillarity disruption (MCCD from now onward). MCCD is a value lying between the minimal water potential of soil and the Briggs-Shantz wilting coefficient. It denotes the water content, at which moisture mobility and conductivity sharply decrease. In thuja plantations, the indexes of volumetric heat capacity and thermal conductivity in the upper soil horizon were minimal. In the illuvial horizon, these indexes were 42% and 12% higher, respectively. However, the uniform distribution of moisture in the soils that grow thuja has equalized thermal diffusivity in the AB and B horizons. Overall, the soil profile of rowan plantations contained less moisture than that of lilac and thuja plantations. Therefore, the volumetric heat capacity and thermal conductivity were lower, since they corresponded to the soil moisture content.

Keywords: Chernozem · Lilac · Rowan · Thuja · Temperature · Humidity · Heat capacity · Thermal diffusivity · Thermal conductivity

1. Introduction

The hydrothermal regimes of soil profiles determine the viability of plant growth and development, including that of trees and ornamental plants. However, there is no data on the accumulation and transfer of moisture and heat in plantations of Meyer lilac, “Alaya” rowan, and dwarf thuja “Danica,” especially concerning the soils of South-Western Siberia [1, 6]. This allowed us to obtain full information on the development of heat and moisture regimes in specific soils, ordinary chernozems and leached chernozems in particular. Moreover, it permitted us to examine the effect of shrub plants on the heat and moisture properties of soils. All of this is needed to develop new reclamation techniques of introducing valuable deciduous and coniferous ornamental plants to the Barnaul arboretum.
2. Materials and Methods
This study aims to examine the thermophysical properties of chernozems and their dependence on soil moisture and grown plants. In this study, we researched ordinary and leached chernozems occupied by lilac, rowan, and thuja plants. The observations were carried out in 2017–2019, in the arboretum of the “M.A. Lisavenko Scientific-Research Institute of Horticulture of Siberia,” which belongs to the “Federal Altai Scientific Center for Agrobiotechnology”. In this paper, we present the results obtained in 2019. We employed the gravimetric method to determine soil moisture content [9]. To determine the thermophysical coefficients, we used the pulse method in the laboratory and the cylindrical probing method in the field [2, 3, 7].

3. Results
We observed ordinary chernozems growing “Alaya” rowan and leached chernozems growing Meyer lilac and “Danica” thuja in May–August 2019. These plants are ornamental shrub species. Dwarf Thuja occidentalis “Danica” is a coniferous photophilic evergreen shrub, up to 60 cm high. Meyer lilac is a dwarf shrub, no higher than 65 cm, with a compact rounded crown. “Alaya” rowan is a beautiful shrub with a sprawling crown and extensive root system. All these plants tolerate frost well.

Table 1 presents the observations of the thermophysical properties of chernozems growing ornamental plants during the growing season of 2019.

| Date  | 10.05 | 27.05 | 12.06 | 27.06 | 15.07 | 30.07 | 12.08 | 29.08 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| T     | 5     | 9     | 6     | 16    | 15    | 22    | 26    | 14    |
| Hor. A, 0–20 cm, ρ = 1,200 kg/m³ | | | | | | | | |
| Cρ    | 2.696 | 2.612 | 2.342 | 2.276 | 2.234 | 2.738 | 2.270 | 2.203 |
| α     | 0.430 | 0.429 | 0.401 | 0.454 | 0.441 | 0.449 | 0.454 | 0.441 |
| λ     | 1.160 | 1.12  | 1.302 | 1.033 | 0.986 | 1.230 | 1.030 | 0.970 |
| U     | 24.9  | 23.3  | 38.0  | 15.3  | 14.0  | 26.3  | 15.0  | 13.6  |
| Hor. AB, 40–50 cm, ρ = 1,090 kg/m³ | | | | | | | | |
| Cρ    | 1.867 | 2.455 | 2.791 | 2.161 | 2.174 | 1.850 | 1.699 | 2.413 |
| α     | 0.538 | 0.459 | 0.428 | 0.493 | 0.493 | 0.536 | 0.577 | 0.468 |
| λ     | 1.004 | 1.128 | 1.194 | 1.065 | 1.072 | 0.991 | 0.981 | 1.130 |
| U     | 17.0  | 31.1  | 38.5  | 23.9  | 24.3  | 16.6  | 13.0  | 20.4  |
| Hor. B, 70–80 cm, ρ = 1,310 kg/m³ | | | | | | | | |
| Cρ    | 2.617 | 3.499 | 3.667 | 3.247 | 3.163 | 2.911 | 2.533 | 2.827 |
| α     | 0.405 | 0.391 | 0.388 | 0.387 | 0.398 | 0.402 | 0.406 | 0.499 |
| λ     | 1.061 | 1.368 | 1.421 | 1.259 | 1.258 | 1.171 | 1.028 | 1.411 |
| U     | 23.2  | 33.8  | 37.9  | 27.5  | 26.0  | 20.2  | 10.8  | 18.1  |

Note: Cρ, 10^6 J/(m³·K) – volumetric heat capacity; α, 10^-6 m²/s – thermal diffusivity; λ, W/(m·K) – thermal conductivity; U, % – water content; T, °C – air temperature at 9:00.

Source: Compiled by the authors.

Table 1 shows that the first half of the 2019 summer period was quite cold. Only at the end of June, the morning air temperature (9:00–10:00) reached 16 °C. In the second half of July, it exceeded 20 °C. Therefore, we conclude, it did not affect the development of the thermophysical regime of chernozem. Mainly soil moisture and the properties of growing plants influenced it [8].

By analyzing the data of Table 1, we concluded that the soil moisture in lilac-growing chernozem was distributed unevenly both between the soil horizons and over time. In A1, the humus horizon, the maximum water content was observed on June 12 (38% of the soil mass), and the minimum from late
June to mid-July, and in August. In AB, the transitional horizon, from late May to mid-July, the humidity did not drop below 24%. In B, the illuvial horizon, moisture content was higher than in the overlying horizons during the entire growing season, except for August 12, when the moisture content was 10.8%.

Thermophysical coefficients changed with the water regime. The sample maximums of volumetric heat capacity and thermal conductivity were observed on June 12. These values reached $3.667 \times 10^6$ J/(m$^3$·K) and 1.421 W/(m·K) in the denser B horizon. The sample minimums of these values were registered on August 12 in the transitional horizon AB. They amounted to $1.699 \times 10^6$ J/(m$^3$·K) and 0.981 W/(m·K). Thermal diffusivity remained the highest in AB horizon ($0.577 \times 10^{-6}$ m$^2$/s) at the minimum humidity on August 12. In the illuvial horizon B, its value did not exceed $0.402 \times 10^{-6}$ m$^2$/s throughout the summer.

Table 2 presents the above-mentioned values of the rowan-growing ordinary chernozem.

| Date       | 10.05 | 27.05 | 12.06 | 27.06 | 15.07 | 30.07 | 12.08 | 29.08 |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|
| **Hor. A, 0–20 cm, $\rho = 1,100$ kg/m$^3$** |       |       |       |       |       |       |       |       |
| $C_p$     | 2.029 | 2.019 | 2.701 | 1.903 | 1.930 | 2.407 | 2.281 | 1.819 |
| $\alpha$  | 0.518 | 0.501 | 0.447 | 0.533 | 0.530 | 0.476 | 0.487 | 0.544 |
| $\lambda$ | 1.051 | 1.012 | 1.206 | 1.014 | 1.023 | 1.147 | 1.111 | 0.990 |
| U         | 20.1  | 19.8  | 36.3  | 16.7  | 17.0  | 29.4  | 25.7  | 14.6  |
| **Hor. AB, 40–50 cm, $\rho = 990$ kg/m$^3$** |       |       |       |       |       |       |       |       |
| $C_p$     | 1.885 | 1.759 | 1.885 | 1.591 | 1.843 | 1.801 | 1.864 | 1.738 |
| $\alpha$  | 0.573 | 0.599 | 0.579 | 0.638 | 0.582 | 0.589 | 0.575 | 0.602 |
| $\lambda$ | 1.081 | 1.053 | 1.091 | 1.015 | 1.072 | 1.060 | 1.071 | 1.043 |
| U         | 25.6  | 23.2  | 26.3  | 19.1  | 24.7  | 23.7  | 25.5  | 22.5  |
| **Hor. B, 70–80 cm, $\rho = 1,230$ kg/m$^3$** |       |       |       |       |       |       |       |       |
| $C_p$     | 2.639 | 2.765 | 2.660 | 2.681 | 2.597 | 2.370 | 2.807 | 2.572 |
| $\alpha$  | 0.432 | 0.423 | 0.429 | 0.427 | 0.431 | 0.443 | 0.431 | 0.430 |
| $\lambda$ | 1.141 | 1.170 | 1.142 | 1.144 | 1.119 | 1.050 | 1.182 | 1.105 |
| U         | 21.0  | 24.2  | 21.5  | 22.3  | 20.2  | 14.6  | 24.9  | 19.4  |

*Note*: $C_p$, $10^6$ J/(m$^3$·K) – volumetric heat capacity; $\alpha$, $10^{-6}$ m$^2$/s – thermal diffusivity; $\lambda$, W/(m·K) – thermal conductivity; U, % – water content.

*Source*: Compiled by the authors.

The moisture content of rowan-growing soils in southwesterly aspects was lower than in lilac-growing soils. Its maximum value was 36.3% of the total soil mass in the horizon A on June 12. During the rest of the growing season, it was lower than 30% across all horizons. The moisture in the transitional and illuvial horizons changed insignificantly, staying in the range of 20%–26%. Water content fluctuated more significantly in the humus horizon. In the end of June – the middle of July, the moisture content was 17%, but it decreased to 14.6% by the end of August. Such moisture distribution corresponds to the slope aspect and the features of rowan, which reached a height of 5 meters and had a well-branched root system. This allowed the plant to transpirate more efficiently, decreasing the moisture content in the soil, especially if compared to soils that grew lilac and thuja.

In rowan-growing chernozem, the thermophysical coefficients and humidity fluctuated weaker, especially in the underlying horizons AB and B. The minimum thermal capacity and conductivity values were observed in the transitional horizon ($1.885 \times 10^6$ J/(m$^3$·K)). The maximum thermal diffusivity value was registered on the same horizon and reached $0.638 \times 10^{-6}$ W/(m·K), which corresponded to the values close to MCCD. This index was fairly constant in the lower levels, fluctuating only by 2% in the illuvial horizon.

The thermophysical features and moisture content of the thuja-growing leached chernozem are
presented in Table 3. This soil profile contained significantly more water, especially in the illuvial horizon. Moreover, the density of the humus horizon here was minimal at 980 kg/m³.

**Table 3.** The dynamics of thermophysical coefficients of thuja-growing leached chernozem in summer 2019.

| Date | 10.05 | 27.05 | 12.06 | 27.06 | 15.07 | 30.07 | 12.08 | 29.08 |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| Hor. A, 0–20 cm, $\rho = 980$ kg/m³ | | | | | | | | |
| $C_p$ | 1.957 | 2.041 | 1.957 | 1.930 | 1.369 | 2.209 | 1.705 | 1.327 |
| $\alpha$ | 0.566 | 0.549 | 0.558 | 0.559 | 0.709 | 0.522 | 0.616 | 0.711 |
| $\lambda$ | 1.107 | 1.121 | 1.092 | 1.078 | 0.970 | 1.154 | 1.050 | 0.944 |
| $U$ | 29.2 | 31.3 | 29.0 | 28.7 | 15.0 | 35.0 | 22.7 | 13.8 |
| Hor. AB, 40–50 cm, $\rho = 1170$ kg/m³ | | | | | | | | |
| $C_p$ | 2.388 | 2.493 | 2.728 | 2.661 | 2.157 | 2.724 | 2.535 | 2.283 |
| $\alpha$ | 0.440 | 0.429 | 0.412 | 0.416 | 0.459 | 0.413 | 0.426 | 0.447 |
| $\lambda$ | 1.050 | 1.070 | 1.124 | 1.107 | 0.989 | 1.124 | 1.109 | 1.102 |
| $U$ | 21.5 | 24.0 | 29.6 | 27.9 | 15.9 | 29.5 | 25.1 | 19.0 |
| Hor. B, 70–80 cm, $\rho = 1220$ kg/m³ | | | | | | | | |
| $C_p$ | 2.630 | 3.050 | 3.071 | 3.155 | 2.739 | 3.025 | 2.685 | 2.701 |
| $\alpha$ | 0.433 | 0.412 | 0.412 | 0.410 | 0.429 | 0.412 | 0.429 | 0.431 |
| $\lambda$ | 1.164 | 1.257 | 1.268 | 1.293 | 1.175 | 1.246 | 1.151 | 1.163 |
| $U$ | 21.6 | 31.8 | 32.5 | 34.5 | 24.6 | 31.4 | 23.3 | 23.7 |

*Note:* $C_p$, $10^6$ J/(m³·K) – volumetric heat capacity; $\alpha$, $10^{-6}$ m²/s – thermal diffusivity; $\lambda$, W/(m·K) – thermal conductivity; $U$, % – water content.

*Source:* Compiled by the authors.

The volumetric heat capacity and thermal conductivity of the upper soil horizon were quite low. At 35% soil moisture, volumetric heat capacity was $2.209 \times 10^6$ J/(m³·K), and thermal conductivity was 1.154 W/(m·K). On June 27, the volumetric heat capacity of the illuvial horizon reached $3.155 \times 10^6$ J/(m³·K), and the thermal conductivity reached 1.293 W/(m·K), at the humidity of 34.5%. Of all studied variants and genetic horizons, the extreme value of thermal diffusivity was observed in the humus horizon A in of thuja-growing soils. It was equal to $0.709 \times 10^{-6}$ m²/s. The uniform distribution of moisture in thuja-growing soils equalized the thermal diffusivity of AB and B horizons.

The soil profile in rowan plantations contained less moisture compared to other samples. Therefore, the values of thermophysical coefficients were lower also, since they are directly affected by the water contents.

The processes of solar insolation, heat accumulation, and heat transfer depend on the genetic and physical properties of soils, weather conditions in the growing season, and the plants that grow in those soils. Knowing the effect that ornamental cultures have on the soil may allow one to study heat exchange and accumulation in arboretum soils. It will also help develop a system for managing the reserves of heat and moisture in the chernozem soil profile and create the optimal conditions for growing ornamental plants.

### 4. Conclusion

In the lilac-growing leached chernozem, the thermophysical parameters changed with the water regime. The sample maximum values of the volumetric heat capacity and thermal conductivity were observed in the dense illuvial horizon – $3.667 \times 10^6$ J/(m³·K) and 1.421 W/(m·K), respectively. The sample minimums were registered in the AB horizon. The thermal diffusivity was the highest in the less dense horizon AB at the lowest moisture content.

In rowan plantations, the water content in transitional and illuvial horizons AB and B changed insignificantly. Such moisture distribution corresponds to the slope aspect and the features of rowan, which reached a height of 5 meters and had a well-branched root system. In rowan-growing chernozem,
the thermophysical coefficients and humidity fluctuated slightly, especially in the underlying horizons AB and B. The maximum thermal diffusivity value was registered on the same horizon and reached $0.638 \times 10^{-6} \text{ W/}(\text{m} \cdot \text{K})$, which corresponded to the values close to MCCD.

In thuja-growing soils, the volumetric heat capacity and thermal conductivity of the upper soil horizon were lower than $2.209 \times 10^6 \text{ J/(m}^3 \cdot \text{K)}$ and $1.154 \text{ W/(m} \cdot \text{K)}$, respectively. In the illuvial horizon, these indexes were 42% and 12% higher. The thermal diffusivity in the humus horizon A was $0.709 \times 10^{-6} \text{ m}^2/\text{s}$. The uniform moisture distribution in thuja-growing soils equalized the thermal diffusivity of AB and B horizons.

The soil profile in rowan plantations contained less moisture compared to other samples. Therefore, the volumetric heat capacity and thermal conductivity were also lower, since they correspond to the soil moisture content.

References

[1] Abaimov V F 2009 Dendrology (Moscow, Russia: Publishing center “Academy”)
[2] Bolotov A G 2015 Method for determining soil thermal conductivity Bulletin of Altai State Agricultural University 7(129) pp 74-79
[3] Bolotov A G, Makarychev S V, and Bekhovykh Iu V 2001 Electronic soil temperature meter. In the collection of scientific papers: Problems of nature management in the Altai (Barnaul, Russia: Altai State Agrarian University)
[4] Geiger P 1960 Climate of the surface layer of air (Moscow, USSR: Foreign literature publishing house)
[5] Kaurichev I S, Aleksandrova L N, Panov N P, Grechin I P, Poddubnyi N N, Rozov N N … Stratonovich M V 1982 Pedology (Moscow, USSR: Ear)
[6] Kolesnikov A I 1974 Decorative dendrology (Moscow, USSR: Forest industry)
[7] Shein E V, Bolotov A G, Mazirov M A, and Martynov A I 2017 Modeling of the thermal regime of the soil by the amplitude of the surface air temperature Agriculture 7 pp 24-28
[8] Trofimov I T, Makarychev S V, and Ivanov A N 2006 The use of lime for liming of soils of Western Siberia Fertility 4(31) pp 15-16
[9] Vadiunina A F, and Korchagina Z A 1986 Methods for studying the physical properties of soil (Moscow, USSR: Agropromizdat)
[10] Zinchenko S I, Mazirov M A, and Zinchenko M K 2008 Soils and plants (Moscow, Russia: Russian Academy of Agricultural Sciences)