Effects of thermal and hydrophysical properties of sandy Haplic Podzol on actual evapotranspiration of spring wheat

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Abstract: The objectives of the research were to: (1) assess the strength of relationships between the soil thermal and hydrophysical properties, (2) evaluate the strength of association of evapotranspiration of spring wheat crop with soil thermal and hydrophysical properties, and (3) estimate the ranges of the thermal and hydrophysical properties of the sandy Haplic Podzol during the growing period of spring wheat in 2022. The study included instrumental simultaneous measurements of meteorological data, soil water retention curve, soil moisture content (SMC) and thermal properties. Actual evapotranspiration was calculated according to the Allen equation. Spearman’s rank correlation coefficients showed that the increase in SMC from 0.10 cm$^3$ cm$^{-3}$ to 0.26 cm$^3$ cm$^{-3}$ resulted in a significant increase in thermal conductivity ($r = 0.81, p < 0.001$), volumetric heat capacity ($r = 0.93, p < 0.001$) and thermal diffusivity ($r = 0.94, p < 0.001$). Actual evapotranspiration also rose with the increasing SMC ($r = 0.91, p < 0.001$) and matric water potentials ($r = 0.61, p < 0.05$). As a consequence of the changes in SMC, the Spearman’s rank correlation coefficients supported the strong positive relationships of actual evapotranspiration with volumetric heat capacity ($r = 0.97, p < 0.001$), thermal conductivity ($r = 0.96, p < 0.001$) and thermal diffusivity ($r = 0.96, p < 0.001$). Pearson correlation coefficients also supported the strong input of thermal inertia to the actual evapotranspiration ($r = 0.88, p < 0.01$). During the whole period of observations, actual evapotranspiration varied from 0.05 to 0.59 mm hr$^{-1}$, soil thermal conductivity – from 0.225 to –1.056 W m$^{-1}$ K$^{-1}$, volumetric heat capacity – from 1.057 to 1.889 MJ m$^{-3}$ K$^{-1}$, heat diffusivity from 0.189 to 0.559 mm$^2$ s$^{-1}$, and thermal inertia – from 516 to 1412 J m$^{-2}$ K$^{-1}$ s$^{-0.5}$.

Keywords: Soil; Thermal properties; Hydrophysical properties; Actual evapotranspiration.

INTRODUCTION

In the surface boundary layer, actual evapotranspiration is one of the important factors because it is a component of water balance affecting crop yields (Allen et al., 1998; Lang et al., 2017; Yang and Zhou, 2011). Evapotranspiration is the combination of evaporation and transpiration, where evaporation is vaporization from the soil surface and transpiration is plant water absorption from the root zone (Nolz, 2016). A better knowledge of evapotranspiration is important for a better understanding of heat balance and water cycle in the system of soil–plants–surface boundary layer (Acreman et al., 2003; Talebmorad et al., 2020). Due to evapotranspiration, a great portion of solar radiation can be transformed into latent heat and sensible heat fluxes, as well as into heat flux in the soils, with the latter significantly affecting the surface heat balance.

Rates of evapotranspiration depend on soil moisture content (SMC), surface resistance, vegetation condition, radiation budget, air insufficient humidity, and wind velocity (Ji et al., 2017; Monteith, 1965; Sun et al., 2019). Soil moisture contributes to the exchange of energy and water between land and atmosphere (Dirmeyer et al., 2000; Haghhighi et al., 2018). Evapotranspiration decreases with decreasing SMC, which can result in increased sensible heating of the surface boundary layer (Berg et al., 2014; Seneviratne et al., 2010). Transitions between different evapotranspiration regimes regulate the development of the surface boundary layer (Feldman et al., 2020). The actual evapotranspiration can be also calculated with reasonable accuracy using the FAO-56 Penman-Monteith equation and FAO specific crop coefficients (Allen et al., 1998).

Such thermal properties as thermal conductivity, volumetric heat capacity and thermal diffusivity are responsible for heat flow and retention processes in soils (Heitman et al., 2010; Verhoeof, 2004). Studies of the thermal properties are needed for understanding and modelling water and energy processes in the soil-plant-atmosphere system (Dong et al., 2015; Yang and Zhou, 2011). Soil water and heat movement are related strongly to soil thermal properties. These thermal properties are required in agronomy, soil science and meteorology as they affect plant growth, microbial activity, water transport and retention, and microclimate in the system of soil–plants–surface boundary layer. SMC, soil porosity (bulk density) and soil temperature have significant impact on the above-mentioned thermal properties (Abu-Hamdeh and Reeder, 2000; Arkhangel'skaya, 2020).

Soil temperature is one of the most important factors governing the exchange of energy and water between the soil and the atmosphere in the surface boundary layer. The temperature affects plant growth, soil hydrophysical, biological and physico-chemical processes (Abu-Hamdeh and Reeder, 2000; Onwuka and Mang, 2018). The thermal conductivity shows a rate of transfer of quantity of heat in a unit volume of soil per unit change in temperature by conduction (Bristow, 2002). The volumetric heat capacity demonstrates the amount in heat change in a unit volume of soil per unit change in temperature (Hansson et al., 2004). The thermal conductivity and the volumetric heat capacity of soil increase with increasing SMC (Abu-Hamdeh and Reeder, 2000; Campbell et al., 1991). As a result, the actual evapotranspiration can also increase with the increasing thermal conductivity and the volumetric heat capacity being affected by the increasing SMC. The thermal diffusivity (ratio of thermal
conductivity to heat capacity) demonstrates how fast soil temperature can change (Hanson et al., 2000). Soil thermal diffusivity is a key indicator of variation in the soil temperature. The reduction in the soil thermal diffusivity may also result in the increase in soil temperature (Zhao et al., 2016). Hanks (1992) reported that measured soil thermal diffusivity for loams remained almost constant with the increasing volumetric SMC from 0.05 to 0.3, while both the thermal conductivity and the heat capacity doubled in magnitude.

Novelty of these studies is that the results of the joint multidisciplinary assessment of evapotranspiration and all the above-mentioned soil thermal and hydrophysical properties are not available for the region of study in Russia. Up to now, the lack of these results was induced by the absence of modern equipment for simultaneous measurements of soil thermal and meteorological properties in the surface boundary layer.

Therefore, the objectives of the research were to: (1) assess the strength of the relationships between the soil thermal and hydrophysical properties, (2) evaluate the strength of association of evapotranspiration of spring wheat crop with the soil thermal and hydrophysical properties, and (3) estimate the possible ranges of the thermal and hydrophysical properties of the sandy Haplic Podzol under different weather conditions during the growing period of spring wheat.

**MATERIALS AND METHODS**

**Study site and measurements**

The study was conducted at the experimental station of the Agrophysical Research Institute in the St. Petersburg region of Russia (59°34'N, 30°08'E) in 2022. The studied soil was a sandy Haplic Podzol (IUS Working Group WRB, 2022) and contained 91.7% of sand, 5.2% of silt and 3.1% of clay particles. In 2022, a small-scale field experiment was established on a plot (48 m²) with spring wheat (*Triticum aestivum L.*) which was sown on 7th of May. Disturbed soil samples (from 0–10 cm soil layer) were collected and field measurements of the soil properties and meteorological parameters were conducted on eight occasions from 12th of May to 4th of August.

For the whole period of observations, the average daily air temperature was 15.4 °C, with the highest and the lowest daily air temperatures recorded, respectively, on 27th of June (24.8 °C) and 17th of May (6.8 °C). The total amount of rainfall for the period of the study was 400.2 mm with the highest daily amount (71.3 mm) measured on 2nd of August. A drought weather conditions (with no precipitation) lasted for 14 days with an average daily air temperature of 19.7 °C.

The surface temperatures were measured by the Compact-Infrared Thermometer Optris CL LT15 (OPTCLT 15) from 11 a.m. to 4 p.m. with about 15-min interval. The average surface temperatures at different measurements occasions are given in Table 1.

Pressure plate apparatus (SoilMoisture Equipment Corp., USA) was used to quantify the relationship between the soil matric water potentials (from –5 kPa to –300 kPa) and SMC. The collected soil samples were air-dried and sieved through a sieve with a 2-mm diameter of openings. Afterwards the soil samples were placed in steel rings (12.57 cm³ in volume), saturated with water and water retention curve was determined according to the Soil Survey Laboratory Methods Manual (1996).

Soil thermal properties: thermal capacity, volumetric thermal conductivity and diffusivity were determined using portable Tempos Thermal Properties Analyzer with the SH-3 dual needle sensor (1.3 mm diameter, 3 cm long and 6 mm spacing, 10% accuracy, Decagon Devices, Inc., Pullman, WA). The measurements of the thermal properties in the top 3-cm soil layer were made every 15 minutes from 11 a.m. to 4 p.m. The SH-3 sensor measures volumetric heat capacity, thermal conductivity and diffusivity in ranges of 0.5–4.2 MJ m⁻³ K⁻¹, 0.02–2 W m⁻¹ K⁻¹ and 0.1–1 mm² s⁻¹, respectively. The sensor performance was verified using a two-hole Delrin block with known thermal properties. The calibration of SH-3 sensor was carried out in the Decagon Devices Inc. (Pullman, WA) and, for instance, was presented by Oyeyemi et al. (2018).

To measure SWC disturbed soil samples were collected from the 0–10 cm soil layer and dried in an oven at a temperature of 105 °C for 24 h. Then the gravimetric soil water content was calculated.

This study did not consider the effects of soil structure on soil thermal and hydrophysical properties and their relationships as the soil was sandy and the soil aggregates were weak and low in content.

**Calculation of actual evapotranspiration**

Assessment of actual evapotranspiration was calculated for the weather conditions during the growing period. The actual evapotranspiration was calculated using the following equation (Allen et al., 2007; Nsiah et al., 2021):

\[ ET_a = \frac{LE}{\lambda} \]

where \( ET_a \) – actual evapotranspiration (mm h⁻¹); \( LE \) – latent heat flux (W m⁻²); \( \lambda \) – latent heat of vaporization (J kg⁻¹); 3600 converts seconds to hours; \( \rho_w \) – density of water ~ 1000 kg·m⁻³ (Allen et al., 2007).

Latent heat of vaporization was calculated using surface temperature (Allen et al., 2007):

\[ \lambda = [2.501 - 0.00236(T_s - 273.15)] \times 10^6 \]

where \( T_s \) – surface temperature (°C), measured with a pyrometer.

The latent heat flux \( (LE) \) was calculated according to the surface energy balance equation (Bastiaansen et al., 1998):

\[ LE = R_n - H - G \]

where \( LE \) – latent heat flux (W m⁻²); \( R_n \) – net radiation (W m⁻²); \( H \) – sensible heat flux (W m⁻²); \( G \) – soil heat flux (W m⁻²). Net radiation \( (R_n) \) was measured with a net radiometer.

Sensible heat flux was calculated as an aerodynamic function (Liu et al., 2007):

\[ H = \frac{\rho_a C_p (T_a - T_s)}{r_a} \]

where \( \rho_a \) – atmospheric density (kg m⁻³); \( C_p \) – specific heat at constant pressure ~ 1013 (J kg⁻¹ K⁻¹) (Allen et al., 1998); \( T_a \) – air temperature at a height of 2 m (°C); \( r_a \) – aerodynamic resistance (s m⁻¹) between two near surface heights – \( z_1 \) and \( z_2 \) (0.1 and 2 m). Air temperature \( (T_a) \) was measured using temperature sensors (DS 1921).

Atmospheric density was calculated using virtual temperature (Allen et al., 1998):

\[ \rho_a = 3.486 \frac{P}{T_{kv}} \]

\( T_{kv} \) – virtual temperature (K); \( P \) – atmospheric pressure (kPa).
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Table 1. Average surface temperatures (T °C) during the period of observations.

<table>
<thead>
<tr>
<th>Date</th>
<th>12.5.22</th>
<th>19.5.22</th>
<th>31.5.22</th>
<th>9.6.22</th>
<th>23.6.22</th>
<th>7.7.22</th>
<th>21.7.22</th>
<th>4.8.22</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>18.4</td>
<td>18.2</td>
<td>18.8</td>
<td>24.6</td>
<td>27.0</td>
<td>27.2</td>
<td>27.8</td>
<td>23.7</td>
</tr>
</tbody>
</table>

Atmospheric pressure was measured with a barometric pressure sensor (MPX4115AP). Virtual temperature was calculated using actual vapour pressure (Allen et al., 1998):

$$T_v = (T_a + 273.15) \left(1 - 0.378 \frac{e_a}{P}\right)^{-1}$$

where $e_a$ – actual vapour pressure (kPa). Actual vapour pressure was calculated using relative humidity (Allen et al., 1998):

$$e_a = \frac{RH}{100} \left(\frac{17.27-T_a}{T_a+237.3}\right)^{1.270.6108 \exp \left(\frac{-237.3}{T_a}\right)}$$

where $RH$ – relative humidity (%) which was measured with relative humidity sensors (HIH-4602-C) at a height of 2 m.

Aerodynamic resistance was calculated as an aerodynamic function (Allen et al., 1998):

$$r_{ao} = \frac{\ln \left(\frac{z_t-d}{z_{ao}}\right) \ln \left(\frac{z_u-d}{z_{ah}}\right)}{k^2 u_t}$$

where $z_t$ – height of wind speed measurements (m); $z_u$ – height of humidity measurements (m); $d$ – zero plane displacement height (m); $z_{ao}$ – roughness length governing momentum transfer (m); $z_{ah}$ – roughness length governing transfer of heat and vapour (m); $k$ – von Karman’s constant = 0.41; $u_t$ – wind speed at height $z$ (m s$^{-1}$), which was measured with a wind sensor (Windgeschwindigkeits sensor) at a height of 2 m.

For a wide range of crops, the zero-plane displacement height, $d$ (m), and the roughness length governing momentum transfer, $z_{ao}$ (m), were estimated from the crop height, $h_c$ (m) by the following equations (Allen et al., 1998):

$$d = \frac{2}{3} h_c$$

$$z_{ao} = 0.123 h_c$$

The roughness length governing transfer of heat and vapour, $z_{ah}$ (m), were calculated according to Allen et al. (1998):

$$z_{ah} = 0.1 z_{ao}$$

Crop height ($h_c$) was measured during the growing season with a measuring tape.

Soil heat flux ($G$) was calculated according to Su (2002):

$$G = R_e \left[\Gamma_c + (1-f_c) \left(\Gamma_s - \Gamma_c\right)\right]$$

where $\Gamma_c = 0.05$ for full vegetation canopy; $\Gamma_s = 0.315$ for bare soil; $f_c$ – fractional canopy coverage. Fractional canopy coverage ($f_c$) was calculated using crop pictures and determination of the vegetation pixels through the predominance of green in the RGB colors. Fractional canopy coverage ($f_c$) was calculated as the area of vegetation to the total surface area. In general, canopy cover is the fractional or percent area of plant canopies projected vertically onto the horizontal ground surface beneath (Guevara-Escobar et al., 2005).

Statistical assessment of the results included the calculation of means and standard deviations. Spearman’s rank correlation coefficients and Pearson correlation coefficients were used to assess strength of associations between the sets of the studied parameters at $p \leq 0.05$. Mann-Whitney U test (Mann and Whitney, 1947) was applied to assess the significance of differences in means (at $p \leq 0.05$), when the normal distribution of data was not confirmed by Shapiro-Wilk test (Shapiro and Wilk, 1965).

RESULTS AND DISCUSSION

Changes in soil moisture content and matric water potentials over time

Figure 1 shows high variations in SMC during the period of observations. The lowest SMC (0.10 cm$^3$ cm$^{-3}$) was recorded on 7th of July. High surface temperatures (>24 °C) and precipitation absence for 14 days resulted in drying of the upper soil layer. The highest SMC (0.26 cm$^3$ cm$^{-3}$) was observed on 4th of August after the heaviest daily rainfall (71.3 mm) on 2nd of August.

The water retention curve of the soil, measured in the laboratory, enabled to quantify the matric water potentials corresponding to the above-mentioned values of SMC. The relationship between the soil matric water potentials and SMC is presented in Figure 2.

Fig. 1. Dynamics of SMC during the period of observations.

The water retention curve of the soil, measured in the laboratory, enabled to quantify the matric water potentials corresponding to the above-mentioned values of SMC. The relationship between the soil matric water potentials and SMC is presented in Figure 2.

Fig. 2. The relationship between the soil matric water potentials (–kPa) and SMC (cm$^3$ cm$^{-3}$). The dotted line shows a possible boundary of the capillary water transition to the film water.
These results have shown that the content of capillary water in the soil varied from 0.26 cm$^3$ cm$^{-3}$ to 0.21 cm$^3$ cm$^{-3}$ at matric water potentials of the soil from –7 kPa to –50 kPa. There was probably a transition of the capillary water to the film water at matric water potentials less than –50 kPa. The water retention curves are affected by the occurrence of soil water hysteresis and by changes in soil structure and bulk density. Pore space analysis indicated that the temporal variability of SWC as affected by wetting (rainfall) and drying cycles was caused mainly by variability of micro- and macro-porosity (Zhang et al., 2017).

The studied sandy Haplic Podzol demonstrated a high volume of macropores which were quickly dried during drying processes. This transition of the soil water forms could result in changes in hydraulic conductivity and thermal properties of the soil.

Figure 3 shows high variations of matric water potentials of the soil during the period of measurements.

Changes in soil thermal properties over time

The preliminary measurements of the thermal properties of the air-dried soil showed that values of the soil thermal conductivity, volumetric heat capacity and diffusivity were equal to 0.194 ± 0.004 W m$^{-1}$ K$^{-1}$, 1.137 ± 0.015 MJ m$^{-3}$ K$^{-1}$ and 0.171 ± 0.001 mm$^2$ s$^{-1}$, respectively. These results correspond to the data presented by Usowicz et al. (2016).

Data on the dynamics of thermal conductivity and volumetric heat capacity are presented in Figure 4.

Soil thermal properties affect heat and water balance in the surface boundary layer, in particular, and, therefore, microclimate in the system of soil–plants–surface boundary layer, as a whole (Usowicz et al., 2016; Verheijen et al., 2013; Xiao et al., 2014). Changes in soil thermal properties are induced by changes in SMC, aeration, bulk density, soil mineralogical composition and organic matter content (Usowicz et al., 2016).

Thermal conductivity of air, water and soil minerals are equal to 0.025 W m$^{-1}$ K$^{-1}$, 0.594 W m$^{-1}$ K$^{-1}$ and 2.5 W m$^{-1}$ K$^{-1}$, respectively. Thermal conductivity of quartz is 7.7 W m$^{-1}$ K$^{-1}$, while for clay particles it is 1.5 W m$^{-1}$ K$^{-1}$. Volumetric heat capacity of air, water, soil solid phase and soil organic matter are equal, respectively, to 0.0012 MJ m$^{-3}$ K$^{-1}$, 4.17 MJ m$^{-3}$ K$^{-1}$, 2.0–2.5 MJ m$^{-3}$ K$^{-1}$, and 2.5 MJ m$^{-3}$ K$^{-1}$.

Fig. 3. Dynamics of the matric water potential (–kPa) of the soil during the period of observations.

Fig. 4. Dynamics of thermal conductivity and volumetric heat capacity of the soil during the period of observations. Bars show standard deviations from means at p ≤ 0.05.

During the period of observations, high variations in SMC were the main factor of the changes in the soil thermal conductivity and volumetric heat capacity. These thermal properties increased with increasing SMC. The Spearman’s rank correlation coefficients demonstrated strong correlations of thermal conductivity (r = 0.81, p < 0.001) and volumetric heat capacity (r = 0.93, p < 0.001) with SMC. These results suggest that thermal conductivity and volumetric heat capacity of the studied soil can be managed by the management of SMC. Zhao et al. (2016) reported that the soil thermal conductivity (r = 0.69, p < 0.001) and volumetric heat capacity (r = 0.79, p < 0.001) were also strongly positively correlated with SMC. Liquid water has the highest volumetric heat capacity and therefore even minor changes in SMC may result in its distinct decrease. In the unsaturated soils, heat transfer through the water menisci is decreasing with a decreasing amount of water that is located in the edges between the contact points of the solid phase. This feature may also affect the average diffusive pathway for water vapor (Bachmann et al., 2001).

Data on the dynamics of thermal diffusivity of the soil are presented in Figure 5.

Fig. 5. Dynamics of thermal diffusivity of the soil during the period of observations. Bars show standard deviations from means at p ≤ 0.05.

Temporal changes in thermal diffusivity (a ratio of thermal conductivity to volumetric heat capacity) reflected changes in SMC, in general, in the content of capillary and that of film
water, in particular. The lowest thermal diffusivity (0.189 mm² s⁻¹) was observed at SMC of 0.10 cm³ cm⁻³ and the highest (0.559 mm² s⁻¹) – at SMC of 0.26 cm³ cm⁻³. The lowest SMC corresponded to the lowest volume of the soil film water while the highest SMC – to the highest volume of the soil capillary (liquid) water. In the area of soil capillary water, at matric water potentials from –7 kPa to –32 kPa, the thermal diffusivity varied approximately from 0.559 mm² s⁻¹ to 0.334 mm² s⁻¹. In the area of soil film water, at matric water potentials from –74 kPa to –300 kPa, the thermal diffusivity varied approximately from 0.274 mm² s⁻¹ to 0.189 mm² s⁻¹. The Spearman's rank correlation coefficients supported strong positive correlation between thermal diffusivity and SMC (r = 0.94, p < 0.001), as well as strong positive correlation of thermal diffusivity with matric water potentials (r = 0.86, p < 0.001).

Data on the dynamics of thermal inertia of the soil are presented in Figure 6.

![Figure 6. Dynamics of thermal inertia of the soil during the period of observations.](image)

**Fig. 6.** Dynamics of thermal inertia of the soil during the period of observations.

Thermal inertia of a soil is an important property as it determines the resistance of the soil surface to temperature variations in the surface boundary layer (Zhang et al., 2016). Estimation of thermal inertia distribution on soil surface is also used for evaluating soil surface water content using visible–near infrared (VISNIR) and thermal infrared (TIR) images (Minacapilli et al., 2012). Thermal inertia (J m⁻² K⁻¹ s⁻¹/²) is a function of thermal conductivity and volumetric heat capacity of soils and is being calculated as the square root of the product of these parameters (Nearing et al., 2012). In a broad sense, the thermal inertia of soil is also its ability to store and conduct heat (Cheruy et al., 2017).

The results of our study have shown that the soil, in the values of thermal inertia, did not demonstrate a stable resistance to high variations of the surface temperatures. The high variations of the surface temperature and SMC caused the high variation in the soil thermal conductivity and volumetric heat capacity. The average value of thermal inertia of the soil was equal to 847±265 J m⁻² K⁻¹ s⁻¹/². The studied soil had high content of sand particles mainly consisting of quartz with low thermal inertia. During the period of observations, the lowest thermal inertia of air-dried samples of the sandy Haplic Podzol was equal to 516 J m⁻² K⁻¹ s⁻¹/². According to the report of other authors (Murray and Verhoef, 2007), the lowest thermal inertia of air-dried samples of sandy soil with content of quartz of 92% was equal to 450 J m⁻² K⁻¹ s⁻¹/². Because of high temporal fluctuations of the thermal inertia the Spearman’s rank correlation coefficients demonstrated even negative correlation of thermal inertia with SMC (r = –0.83, p < 0.001) for the whole period of observations. Nevertheless, at the end of the period of studies the thermal inertia increased from 516 J m⁻² K⁻¹ s⁻¹/² to 1412 J m⁻² K⁻¹ s⁻¹/² with SMC increasing from 0.10 cm³ cm⁻³ to 0.26 cm³ cm⁻³. Minacapilli et al. (2012) reported that during the drying phase, the measured thermal inertia values of fine-textured soil decreased from 1500 to 500 J m⁻² K⁻¹ s⁻¹/² as the corresponding measured SMC values decreased from 0.35 to 0.01 m³ m⁻³.

According to Nearing et al. (2012), at high moisture levels, thermal inertia was more sensitive to changes in SMC. Thermal inertia was a better predictor of SMC in moderately wet conditions than in dry conditions due to a lack of sensitivity of thermal inertia to changes in soil moisture at low SMC. In general, the results of the thermal inertia study have shown the increase and high variations in heat supply for spring wheat on the sandy Haplic Podzol for the whole period of measurements.

Data on the evapotranspiration dynamics are presented in Figure 7.

![Figure 7. Dynamics of evapotranspiration during the period of observations.](image)

**Fig. 7.** Dynamics of evapotranspiration during the period of observations.

Actual evapotranspiration also demonstrated a temporal increase and more or less pronounced variations during the period of studies. Nevertheless, a drastic increase in actual evapotranspiration was observed on 5th of June whereas SMC did not show the similar change (Figure 1). The reason for that could be the intensive water uptake by the crop roots from the topsoil (also resulting in a little reduction of soil water reserves), as the water demand of the crop during that intensive growing period was in the increasing phase.

The highest daily rainfall led to the increase of actual evapotranspiration at the end of the study period. During the period of observations, actual evapotranspiration ranged from 0.05 mm hr⁻¹ to 0.59 mm hr⁻¹. The Spearman’s rank correlation coefficients supported a strong positive relationship of evapotranspiration with the SMC (r = 0.91, p < 0.001) and a weaker but significant relationship with matric water potentials (r = 0.61, p < 0.05). Positive strong relationship of evapotranspiration with SMC was induced by soil water availability to spring wheat. The highest availability of soil water to the spring wheat plants was observed in the area of capillary water at matric potentials from –7 to –32 kPa or to –50 kPa, whereas the lowest water availability was recorded at matric potential of –300 kPa corresponding to the amount of soil film water.

Among the thermal properties, the Spearman’s strongest correlation was observed between evapotranspiration and volumetric heat capacity (r = 0.97, p < 0.001) and the weakest strong relationships – with the soil temperature (r = 0.51, p < 0.05). The Spearman’s rank correlation coefficients have also shown strong relationships of evapotranspiration with soil diffusivity (r = 0.96,
p < 0.001) and thermal conductivity (r = 0.96, p < 0.001). The Pearson correlation coefficient also supported the strong input of the thermal inertia as the indicator of crop heat supply to evapotranspiration (r = 0.88, p < 0.01). These results supported the data of other scientists finding positive relationships of evapotranspiration with soil temperature (Ni et al., 2019), soil thermal conductivity and volumetric heat capacity which ensure plants with heat (Nsiah et al., 2021; Wang et al., 2021).

CONCLUSIONS

The results have shown that the joint multidisciplinary studies were useful for a valid and deeper assessment of the strength of relationships between the soil thermal and hydrophysical properties as well as between actual evapotranspiration of spring wheat and thermal and hydrophysical properties. The obtained results have confirmed that soil moisture content and soil thermal properties significantly and positively affect actual evapotranspiration during the growing period of spring wheat on a sandy Haplic Podzol.

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