DOI:10.28974/idojaras.2024.3.3

IDŐJÁRÁS
Quarterly Journal of the HungaroMet Hungarian Meteorological Service
Vol. 128, No. 3, July – September, 2024, pp. 327–344

Assessment of soil microclimate in an urban park of Budapest, Hungary

Malek Abidli[1], **Gábor Halupka**[2,3,*], and **István Waltner**[2]

[1] *Hungarian University of Agriculture and Life Sciences*
Doctoral School of Environmental Sciences
2100 Gödöllő, Páter K. u. 1., Hungary

[2] *Hungarian University of Agriculture and Life Sciences*
Institute of Environmental Sciences,
Department of Water Management and Climate Adaption
2100 Gödöllő, Páter K. u. 1., Hungary

[3] *Mining and Geological Survey of Hungary*
1145 Budapest, Columbus street 17–23., Hungary

* *Corresponding Author E-mail: Halupka.Gabor.Erno@uni-mate.hu*

(Manuscript received in final form September 9, 2023)

Abstract— Investigation of urban parks is a particular research section in the frame of urban geology, with increasing social importance. Both natural and anthropogenic factors affect these green sites, giving special scientific importance to their investigation. Thus, the behavior of such a 'composite' system is expected to be quite complex.

Based on the general circumstances, a research project was introduced in 2016 in the former Mining and Geological Survey of Hungary (now: Supervisory Authority for Regulatory Affairs). The ongoing project was focused on the behavior of urban parks. Within the frame of this research, between 2016 and 2019, field studies were started in 4 parks of Budapest. This paper is targeting one of these parks, namely Honvéd square.

Our objective is to understand the behavior of urban parks under special conditions (e.g., during heat island effects) by getting information from well-defined positions. This can be essential to perform more sustainable water management in an urban park.

Within the frame of the field works soil temperature and soil moisture measurements were being recorded manually every week in every park, at four different locations within a park. Observation points were selected to describe the different microclimates of the parks.

A statistical analysis of the data reveals that the urban heat island (UHI) effect is reflected in soil temperatures at a citywide scale and that by moderating urban soil surface temperature extremes, trees and shrubs may help to reduce the adverse impacts of urbanization on microclimate, soil processes, and human health.

It can be stated, that beside the manual measurements, the automated soil temperature detection was significantly influenced by soil depth at the Honvéd square park. At 100 cm below the surface, the soil temperature is relatively constant. It was approved that not only do deeper soil layers undergo less drastic seasonal temperature fluctuations but also the changes taking place lag further behind those of shallower soil layers.

Key-words: urban parks, soil moisture, soil temperature, urban heat island effect, urban geology, general meteorological factors.

1. Introduction

Urban parks are integral parts of the dynamic network of city ecosystems and provide vital environmental services. They support urban populations in an ecological, cultural, social, psychological, and economic context (*Burgess et al.,* 1988; *Conway,* 2000; *Gehl* and *Gemzoe*; 2001, *Grahn*, 1985; *Bowler et al.,* 2010; *Konijnendijk et al*., 2013; *Demuzere et al.*, 2014; *USEPA*, 2017; *Stępniewska*, 2021). Urban parks, unfortunately, often embody the problems of inefficient irrigation use and stormwater runoff. In fact, urban park water management has become a hot subject of growing social significance. If we understand how urban parks behave under special impacts, more effective water management can be performed (*Loures et al*., 2007).

On the other hand, the increasing urbanization of the world's population, which is projected to accelerate in the 21st century (*Angel et al*., 2005), seems to have both beneficial and detrimental effects on citizens and the environment (*United Nations,* 2014). They create their special microclimates as urban areas replace natural habitats with construction materials and anthropogenic activities (*Erell et al*., 2011).

Urbanization changes the climate and results in various climatic features that influence urban residents' everyday lives (*Honjo*, 2009; *Kalnay* and *Cai*, 2003). Urban heat island (UHI) is a phenomenon connected to both climate change and urbanization (*Bowler, et al*., 2010; *Kong et al*., 2016), which identifies urban areas with slightly higher temperatures than the nearby rural areas. Modification of the surface properties of urban areas influences the energy balance at micro- and local scales between the earth and the ambient environment (*Oké*, 1981; *Steward* and *Oké*, 2012). Microclimates can be substantially different from the dominant environment in an area that has high human impact (*Brown* and *Gillespie,* 1995). A healthy microclimate promotes the use of open spaces by the public (*Mahmoud*, 2011; *Thorsson et al*., 2004). Therefore, it is important to explore the factors that directly and indirectly affect microclimates in order to improve outdoor comfort.

Different microclimatic parameters (MPs) may be used in the study of urban microclimates. It can generally be characterized by air temperature (Ta), relative humidity (RH), wind conditions (velocity and direction), mean radiant temperature (MRT), and light intensity (*Li et al.,* 2018; *Honjo*, 2009; *Davies-Colley et al*., 2000).

For a better understanding, in the spring of 2016, the former Mining and Geological Survey of Hungary started a targeted research project on parks in Budapest, aimed at the role of microclimate in the different urban parks of the city. In this paper, we are focusing on one of these investigated parks, the Honvéd square, which is situated east of the Danube river.

The main purpose of the study is to investigate the impacts of microclimate on the urban park and to provide a reference point for the water management of urban green spaces by better understanding the behavior of urban parks under special conditions (e.g., during heat island effects). The detection of the climatic parameters was established through two different methods, a manual detection for soil temperature and soil moisture, and an automated tool through different depths to detect the soil temperature.

2. Materials and methods

2.1. Manual detection at the Honvéd square

The study area is located in the central part of Budapest. The altitude is approximately 30 m, and the daily mean temperature is between -2.5 °C and 32 °C.

The weekly data collected was for the period from August 22, 2016 to September 26, 2019. This data was collected every week on Wednesday at around 11–12 am. The soil temperature and soil moisture data were collected from four different points. The rationale behind the selection of these four points is explained in Section 2.3. Besides these factors, air temperature and precipitation data were also detected. The park was irrigated by the local authorities. The frequency of the irrigation was according to the dry periods.

The instruments used for the manual measurements are as follows:

- Soil thermometer: To detect the soil temperature in the depth of 30 cm, a low budget 320 mm detachable soil and ground thermometer 'NATURE 6080082' was used. The temperature range of the instrument varied between -5 °C and +80 °C. The instrument was produced by NATURE, Holland.
- Soil moisture meter: The use of 'PCE-SMM 1' instrument started on November 16, 2016. Its limit of measurement for moisture content is between 0 and 50%, with an accuracy of ±0.5%. Its optimal operating temperature is between 0 and 50 °C.
- Air temperature measurements: For this purpose, an analog air thermometer was used, with the range of -35 and +50 °C.

2.2. Automated detection at the Honvéd square

In the Honvéd square, four automated soil temperature instruments (H-1, H-2, H-3, and H-4 – naming of the instruments based on the detection points' name) were installed (*Fig. 1*). The instruments have been developed by Ákos Gyenis, an expert in experimental, custom tailored soil detection devices in Pécs, Hungary.

Fig. 1. Detection points at the Honvéd square in Budapest.

The start of the automated measurements was on December 12, 2018, except in the case of H-4, which was eliminated and changed with an another sensor ('H-plus'), because of some unexpected technical problems. Detections of H-plus started on January 17, 2019.

All the equipments took measurements every hour and on 8 different levels: 0, 5, 10, 20, 30, 50, 100, and 200 cm below the surface.

2.3. Detection points

As for the field works, soil temperature and soil moisture measurements were being monitored weekly in the park, at four different locations, and the automated detection of soil temperature was performed on an hourly basis. For better observation, four points were selected to describe the different conditions of the park. The points are:

- Borderline of the park facing the northern frontage of the surrounding houses (H-1);
- A permanent sunny area (H-2);
- A permanent shady area (H-3);
- Borderline of the park facing to the southern frontage of the houses (H-4).

2.4. Limitation of the data detected

There were expected and unexpected gaps in the data series. In the first case holidays, in the latter one the weather was the reason. When the temperature is below zero the soil becomes frozen, so the moisture content could not be measured (in depths close to the surface), and it caused a malfunction of the soil moisture sensor.

2.5. Software used

For the data processing and statistical calculations, R statistical environment was used (*Venables et al.,* 2023), while the data filtering was done in MS Excel 2016.

3. Results

3.1. Analysis of the manual soil temperature and soil moisture detection at the Honvéd square

3.1.1. Soil temperature

The data has shown that the maximum and minimum air temperatures in the park were 32 °C and -2.5 °C, respectively. On the other hand, the soil temperature in the 30 cm below surface (bs) depth showed 28 °C and -1°C for H-1, 27.5 °C and -2.5 °C for H-2, 26 °C and -2 °C for H-3, and finally, 25.5 °C and -3 °C for H-4 as minimum and maximum temperature during the measurement period (*Table 1., Fig .2*).

Table 1. The highest and lowest soil temperature values at the different detection points. Manual measurements.

	H-1	**H-2**	**H-3**	**H-4**
Soil maximum temperature, °C, 30 cm bs	28	27.5	26	25.5
Soil minimum temperature, °C, 30 cm bs	-1	-2.5	2	-3

The data collected during summer 2018 showed the highest soil temperature, meanwhile, the lowest soil temperature could be detected during the winter of 2017.

Fig. 2 presents the general trend of seasonal air temperature and soil temperature in the studied downtown park, during the whole research period (2016–2019). The calculated R^2, which is the coefficient of determination value, comes to 0.0308 for the air temperature, 0.0402 for the shady point (H-3), 0.0282 for the south point (H-4), 0.0658 for the north point (H-1), and 0.0142 for the sunny point (H-2). It means that the variability in the soil temperature during the whole period is as follows: 4.02% for the Shady point, 2.82% for the South point, 6.58% for the North point, and 1.42% for the Sunny point.

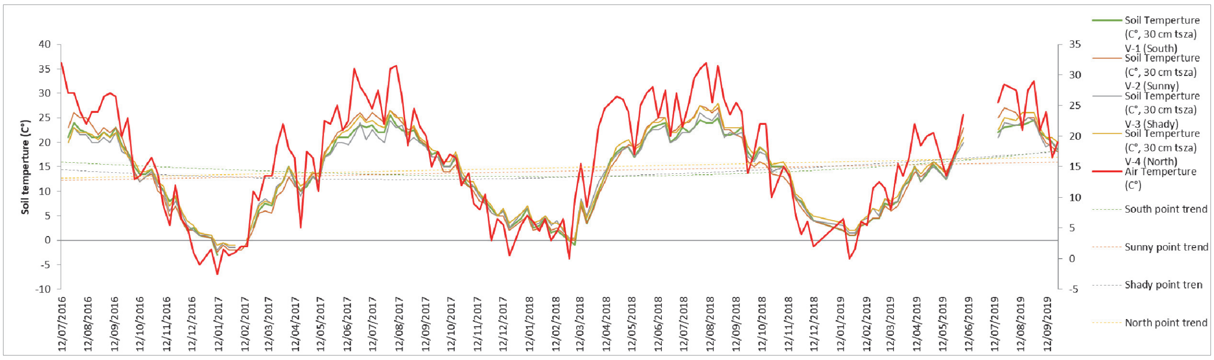

Fig. 2. Change in soil temperature, 30 cm below soil surface at the Honvéd square in Budapest.

Running of curves of the soil temperature presented in *Fig. 2* is different at the four locations. This difference is related not only to the location but also to the season. Furthermore, it is clear that during the summer season, the soil temperatures at 30 cm bs are comparatively higher at the sunny point (H-2) than at the shady point (H-3). In fact, during summer 2019, the soil temperature was 27 °C at the sunny point (H-2) and 25 °C at the shady point (H-3). On the other hand, the soil temperature at the sunny point was still higher than at the northern frontage of the surrounding buildings (H-1) in the summertime.

The results mentioned above support the irrigation effect on the temperature as a cooling factor. Over the years, the greatest UHI effects on soil surface temperature have been observed during the summer months. The vegetation effects are capable of cooling the urban atmosphere and have the ability to reduce the UHI effect and provide proof that this impact applies to the soil system (*Susca et al.*, 2011). Although slightly higher, the cooling impact on the hottest days was indistinguishable from that on the mean summer day. This implies that irrigation has a greater impact on particularly hot days, as a cooling factor than the vegetation.

3.1.2. Soil moisture

When it comes to soil moisture, it was detected manually on a weekly basis, same as air temperature, for the period of August 22, 2016 to September 26, 2019. This data was collected every week on Wednesday at around 11–12 am. Soil moisture was measured at 5–10 cm depth at 4 different detection points: borderline of the park facing the northern frontage of the surrounding houses (H-1), a permanent sunny area (H-2), a permanent shady area (H-3), and borderline of the park facing to the southern frontage of the houses (H-4). The soil moisture detection points were very close to the soil temperature detection points. This means that the soil moisture was measured along a circle in which the center was the soil temperature detection point, and its radius was about 20 cm. According to this approach, we measured the moisture content in five different points, and we considered the average of the five measurements.

Applicability of the soil moisture meter was strongly related to the amount of available liquid water in the soil. It means that when the soil was dry or frozen, the sensor wand could be hardly pushed into the soil, or it became impossible. This physical limitation could be so serious, that gaps appeared in the data series.

Although not very apparent from the data presented here, the relationship between these two factors (air temperature and amount of water used for irrigation) probably works both ways. This means that low soil moisture content leads to a higher temperature, because of the lack of the cooling effect (*Al-Kayssi*, 1990). In addition, high temperature undoubtedly accelerates soil drying, resulting in lower soil moisture content. On the other hand, soil moisture came to its minimum during fall 2018, the soil moisture detected at the 4 detection points was 0%, 7.84%, 0%, and 0.56%, respectively (*Fig. 3*). The high soil moisture content among the 4 mentioned points was measured at the sunny point (H-2), due to its exposed position to fall precipitation and with no vegetation cover.

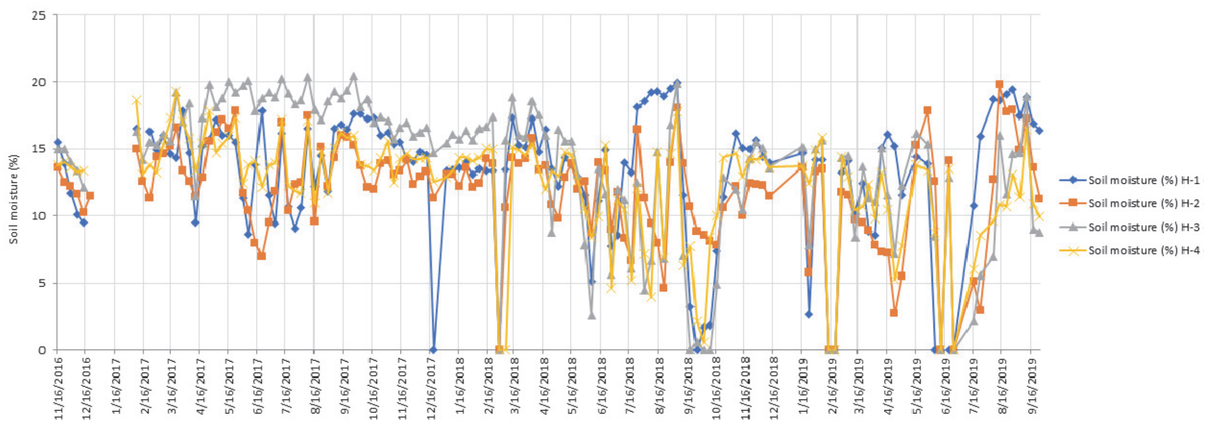

Fig. 3: Changes in soil moisture, 5 cm below soil surface at the Honvéd square in Budapest.

Soil moisture is an important control on heat and water transfer between the land and atmosphere, which in turn affects the development of extreme heat events (*Vogel et al*., 2018). In fact, the soil moisture in the 4 detection points is different especially during summer (see *Fig. 3*). However, the soil moisture at the sunny detection point is more influenced by solar radiation, even during the winter, and the persistence of soil moisture at the sunny detection point was slightly lower than at the shady detection point.

It is obvious that soil temperature and soil moisture are not independent of each other. Analysis of the intrinsic connection between soil temperature and soil humidity can help to understand the possible water management interactions in the park. In other words, soil moisture affects the water supply of the vegetation.

3.2. Analysis of the automated soil temperature detection at the Honvéd square

The air temperature was only measured on a weekly basis in our research (*Fig. 2*). As we mentioned, the soil temperatures at each detection point were measured by automated instruments, as well, at different depths of 0, 5, 10, 20, 30, 50, 100, 200 cm below the surface. We marked the sensors in the different depths, as T1, ..., T8, where T1 belongs to the deepest detection (200 cm), T2 to 100 cm, T3 to 50 cm, ..., and T8 to 0 cm (surface).

The sensors recorded data every hour and were stored in onboard memory. Then, the stored data was read out by a laptop on the spot. The soil temperature was measured for 135 days, 7 hours, from December 12, 2018 at 15:00 UTC to July 30, 2019 at 08:00 UTC. Due to unexpected technical reasons, the detection instrument H-4 had to be replaced by a new one (called H-plus), and the start of the measurement began on January 17, 2019 at 10:00 UTC. Other technical problems also happened during the detection period. The H-2 detection measurement records had multiple abrupt drops of temperature during the warmer months. These errors are so strong and frequent that they reached the 0 °C – which means that the data was not usable for the period in question (*Fig. 4*).

This phenomenon does not exist in plots of H-1, H-3, and H-plus. After consultation with the expert who built the instruments, he believed that the data collector device had some problem when the outer temperature exceeded a threshold value. This is why we ignored to use this data series in the analyses.

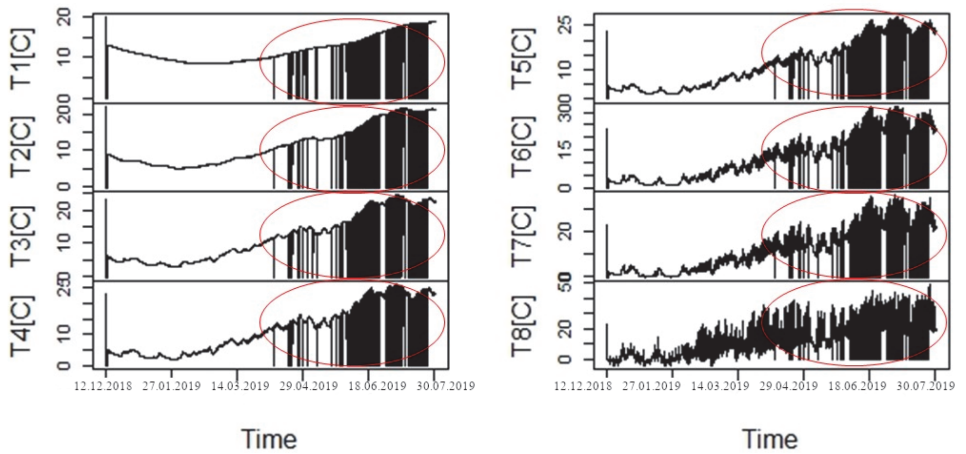

Fig. 4. Technical problems at the measurement point H-2: A severe drop in temperature can be observed during summer 2019 (problems are indicated by red ellipses)

3.2.1. Annual scale

Based on *Table 2*, the minimum and maximum soil temperatures at the different depth at H-1 were -4.99 °C (December 20, 2018, midnight, surface), and 34.52 °C (July 1, 2019, 17:00, surface). At H-3 it was -4.16 °C (December 20, 2018 from midnight until 01:00) and 32.78 °C (July 1, 2019 at 17:00). Finally, at H-plus it was measured as -2.02 °C (January 23, 2019 at midnight) and 32.2 °C (June 13, 2019 at 15:00).

Table 2. Summary of the statistics related to the annual automated soil temperature detections at the park of Honvéd square, Budapest

	Minimum	**Maximum**	**Median**	**Mean**	**Standard deviation**
H-1	-4.99	34.52	11.08	11.00	6.71
H-3	-4.16	32.78	11.41	11.12	6.68
H-plus	-2.02	32.2	12.66	12.79	6.49

Results from soil temperature sensors have revealed (*Fig. 5*) that the highest and lowest measured soil temperatures occur at the surface, and fluctuations in soil temperature are more frequent in the topsoil than in the lower soil layers.

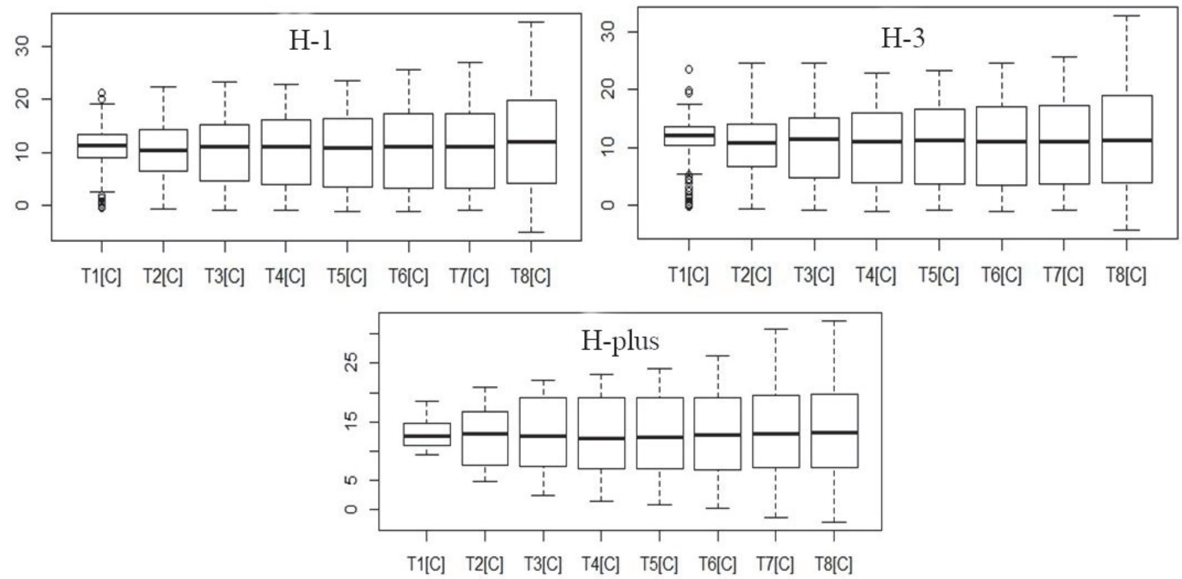

Fig. 5. Box and whisker plot of the annual soil temperature at the different depths (T1 – 200 cm, T2 – 100 cm, T3 – 50 cm, T4 – 30 cm, T5 – 20 cm, T6 – 10 cm, T7 – 5cm, and T8 – 0 cm).

The annual mean and standard deviation of the soil temperature at the different depths were 11.00 °C and 6.71 °C for H-1, 11.12 °C and 6.68 °C for H-3 and 12.79 °C and 6.49 °C for H-plus. Also, the median was 11.08 for H-1, 11.41 for H-3, and 12.66 for H-plus.

We used boxplots to display the soil temperature data distributions, according to the different depths (*Fig. 5*). The boxplots provide additional landmarks describing the distribution of the soil temperature in the different depths (the vertical axis of the box plot is read from the lowest value at the bottom to the highest value at the top). The median relating to the soil temperature is between 11.08 and 12.66 (horizontal line inside the box). The upper and lower ends of the boxes are the hinges (the approximate upper and lower quartiles) of the soil temperature distribution. The vertical lines from the ends of the boxes connect the extreme data points to their respective hinges. The distance from the observation with the smallest value to the largest value represents the range of the data. This is the distance from the left end of the lower whisker to the right end of the upper whisker.

In the 3 boxplot graphs (*Fig. 5*), we can observe different sizes of the boxes, where the deepest depth (T1), have comparatively the shorter plot, while the surface detection (T8) have the taller plot. This indicates that there are minor changes in the soil temperature at 200 cm depth through the year compared to the significant ones detected on the surface. This should make sense, since the surface soil temperature is changing within wide range, resulting lower temperature in winter and higher in summer, than the temperature at the bottom, in the same seasons.

Over the detected year, the soil temperature was aggregated into hourly values. When the soil temperature was consistently below 0 °C, it was documented as frozen condition of the soil, while above 0 °C, it was registered as thawed condition of the soil (*Fig. 6*).

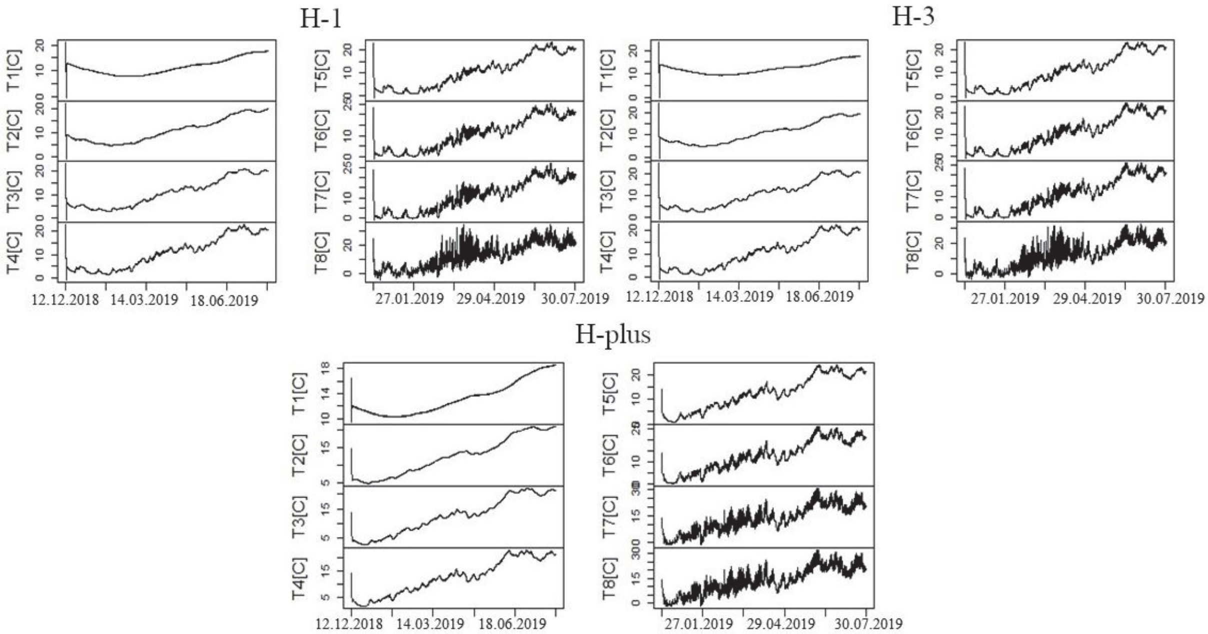

Fig. 6. Time series of the soil temperature at the different layers, at the 3 detection points of the park (T1 – 200 cm, T2 – 100 cm, T3 – 50 cm, T4 – 30 cm, T5 – 20 cm, T6 – 10 cm, T7 – 5cm, and T8 – 0 cm)

In addition to the meteorological factors, the vegetation cover may moderate the response of soil temperature sensors (*Fiebrich* and *Crawford*, 2001). Vegetation plays a role in reducing the heat energy conversion and has a direct effect on the temperature of the soil in different layers (*Chai et al*., 2008). *Chai et al*. (2008) continue by stating that vegetation retains the moisture through the roots contained in the soil, thereby reducing soil evaporation and water loss. They also mention that the degraded vegetation would weaken the cooling impact of plant transpiration on soil temperature and increase water dispersion, ultimately leading to a reduction in soil temperature in deeper depths. According to these cited findings, the bare soil surface of H-2 point retains less soil moisture content than the shady point (H-3), because of the exposed position against the direct heat radiation of the Sun.

A soil-warming trend could be observed during the summer season, but this trend has more “faces” according to the depth. It means, that going by the depth, this change becomes slower, and has less fluctuation (smaller amplitude), compared to the layers closer to the surface. The trend reverses in winter, but the higher temperature fluctuation belongs to the surface layers again (*Fig. 6*). This implies that the warming occurring in the surface layers needs some time to reach the deeper soil layers, but once warmed, the deeper layers remain warmer through the year. Nevertheless, in this time-shifted warming up process, the soil moisture content can play a key role, since dry soil warms up faster than a wet one (*Javier, et al.*, 2018).

However, change of the temperature in the soil profile with the seasons are also interesting, and can be observed in our data. In spring and summer, soil temperature starts to decrease with depth, because the surface layers are able to warm up faster, than the deep layers. In winter, soil temperature increases with soil depth, because the surface soil temperature drops more quickly. In general, the closer we are to the surface, the higher is the rate of temperature change. This process has two peaks throughout the year: a positive one in the warm half-year, and a negative one in the cold half-year. It means that the response of surface soil temperature to the effects of the everyday weather conditions is much more pronounced than that of the deep layers.

The time-shifted, profile depth-linked behavior of the soil temperature has a connection with the seasonal change of the air temperature, as a factor of the local meteorological, but also, regional climatic factor (*González-Rouco et al*., 2003, *Zhang et al.,* 2005).

According to *Brady* and *Weil* (2013), the lower temperatures of water-saturated soil are due, in part, to water evaporation – a process that consumes a lot of heat – and, in part, to high specific heat in water-saturated soil. Keeping in mind that the park is irrigated, this process has an important role in the analysis of the soil temperature at the different depths. However, role of irrigation is also interesting, since it is a seasonal impact, mainly concentrating on the summer (warm half-year). Furthermore, effect of irrigation can be traced much more in the surface layers, than in the deeper ones (*Abdelaziz, et al*., 2022) Furthermore, according to these authors, soil temperature in the few centimeters above saturated soil is usually 3 to 6 °C lower than that of dry soil or slightly moist soil. In studies performed by *Diniz et al.* (2013), the months of lower soil temperatures were precisely the months with higher rainfall.

3.2.2. At a level scale

In this study, it was interesting to analyze the behavior of the soil temperature in the different depths, namely at 0, 5, 10, 20, 30, 50, 100, and 200 cm below the surface. The drillings to install the sensors did not reach the groundwater.

The climate variation in different seasons and months results in a corresponding variation in soil temperature in different depths. The highest, but also the lowest soil temperature was recorded at the 0 cm depth (*Figs. 5* and *6*). The observed data were analyzed for the period from December 12, 2018 to July 30, 2019.

Fig. 7 shows the variation of the hourly mean soil temperature at different depths at three detection points. (*Fig. 6* displays the three detection points' temperature curves, while *Fig. 7* displays the different depth's temperature at the three detection points.) According to the data series, the soil temperature in the Honvéd square park reaches both of its maximum and minimum temperatures at the surface, with 34.52 °C and -4.99 °C, respectively, during July and December. However, going to the depth, more major features can be observed relating to the change of the soil temperature. a.) The amplitude of the change is decreasing with the depth. b.) There is a time shifting in occurrence of the maximum and minimum values: the bigger is the depth, the time shifting will be higher. c.) The maximum temperature values will be lower and lower toward to the deep than the surface temperature, and the minimum values will be higher with the increasing depth. The temperature delay from surface to deeper layers shows that the heatwave requires a certain time to spread in the soil downward because of slow heat conduction capacity through the vertical soil profile, as mentioned above.

Referring to *Figs. 6* and *7,* the maximum soil temperature occurs in July (when cooling demand is high) at a depth of 0 cm (surface), but it also occurs in January at a depth of 100–200 cm below the surface. It clearly shows that the heat transport needs time to reach the deep layers. However, we can also interpret this phenomenon as a "virtual" movement of a specific temperature value along the soil profile.

Characteristic trends were found in December and January at the three different detection points (*Fig. 7*). The most common trend is that the soil temperature at 200 cm below surface is higher than the average of the seven upper soil layers for the three different detection points. This is because of the downward spread of the stored heat energy from the soil surface, and the less seasonal loss with the growing depth.

Trends in change of soil temperatures at 0, 5, 10, 20, 30, 50, 100, 200 cm depths were also analyzed. There was a significant positive trend with soil temperatures in spring and summer means, but not for the winter and annual means (*Fig. 7*). A positive, warming trend with time in soil temperature was detected at all depths below 5 cm, which associated with trend in air temperatures (and so the incoming radiation) over the same period.

As it was shown in the preceding section, temperatures are increasing at every specific level of soil column during the investigated period (from the winter half year toward the summer half year; see *Fig. 7*), and this trend persists in all of the detection points and months to a varying degree, especially during summer months. A plausible explanation for this observation is that soil and atmospheric heat exchange is the fastest at the surface layers (*Hu* and *Feng*, 2004). As explained by *Bai* (2009), heat loss is amplified by surface evaporation leading to cooler soil temperatures within the first 0 to 30 cm depth. Water accumulating in lower depths tends to retain heat compared to the upper surface layers where evaporation accelerates cooling (*Hu* and *Feng* 2004). *Jacobs et al.* (2011) reported that lower soil depths, from 100 cm up to 200 cm, are significantly warmer than layers close to the surface during the cold season.

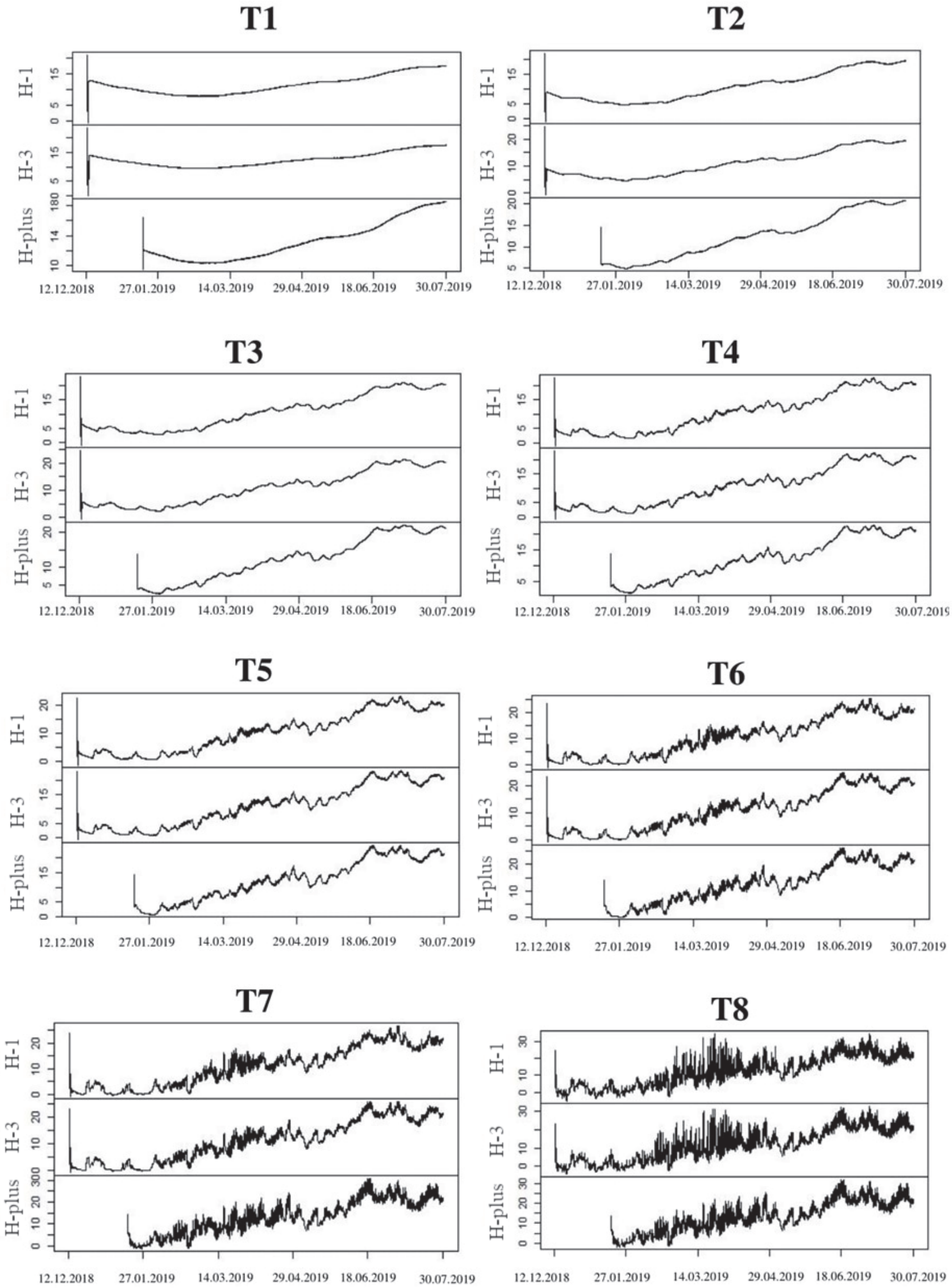

Fig. 7. Time series of the different depths of the automated soil temperature (T1 –200 cm, T2 – 100 cm, T3 – 50 cm, T4 – 30 cm –, T5 – 20 cm, T6 – 10 cm, T7 – 5 cm, and T8 – 0 cm).

The thermal amplitudes studied in the soil for both the hourly and daily mean data showed lower soil temperature variation with increasing depth, regardless of the external variables that affect the increase or decrease in heat emission from the soil.

4. Conclusions

Soil temperature varies from month to month as a function of incident solar radiation, rainfall, seasonal swings in overlying air temperature, local vegetation cover, type of soil, and underground depth. However, it can be also seen, that the effect of the meteorological factors (especially of the temperature) time-shifted with the increasing depth of the soil column.

The stable observable differences among the measurement points within the park indicate that the natural processes in the park are differentiated. This clearly highlights importance of a differentiated park management practice, in terms of a better planned irrigation concept, and preserving of soil moisture by covering the seasonally bare surface (e.g., by mulch).

Due to the much higher heat capacity of soils relative to the air and the thermal insulation provided by vegetation and surface soil layers, seasonal changes in soil temperature deep in the ground are much less than close to the surface and lag significantly behind seasonal changes in overlying air temperature. Thus, by summer, soil temperature in the depth remains cooler than the temperature of the overlying air, and it acts like a natural sink for removing heat from the built and natural environment. This suggests that the heat capacity and speed of heat conductivity of the soil are important factors. This delayed, time-shifted reaction of the soil to the air temperature can be true much more in the deeper parts of the soil section, than in the surface, or even the whole soil column.

Furthermore, a decrease in soil temperature values may be explained by the effect of precipitation on heat conductivity in the soil. When solid particles are surrounded by water, there is an effective increase in the contact surface capable of conduct heat, in addition to the mass flow of soil water. Therefore, thermal conductivity rises quickly and significantly (*Prevedello*, 2010).

Our results have highlighted, that meteorological factors, primarily air temperature and precipitation play a key role for the soil system, as they will influence the soil moisture and temperature data series, producing a seasonal, periodical variability. Effect of these meteorological factors occurs differently according to the depth, so processes of change of the moisture content and temperature show a definite direction at different depths through a year, producing a kind of yearly evolutionary pattern in the data. Soil temperature as a function of time, location, and depth is an important parameter in agronomic, geo-environmental, and geothermal energy applications. In the study, the automated soil temperature detection highlights that the depth significantly influences the soil temperature at the Honvéd square park. More precisely, the amplitude of the seasonal soil temperature changes is decreasing with going to the deep. In addition, the daily temperature changes can be traced only in the layers close to the surface, so the daily change of the soil temperature is shading with going to the deep. Under 100 cm below the surface, the soil temperature is relatively constant. It was proved that not only do deeper soils undergo less drastic seasonal temperature fluctuations but also the changes taking place lag further behind those of shallower soils.

Our results also indicate that the spatial heterogeneity of urban parks can play a significant role in their sensitivity and alleviating capacity regarding the urban heat island effect. In addition, an important consequence of our results is to re-think the daily park maintenance practice, with differentiating the patterns of irrigation, even within a small urban park.

Acknowledgements: This material is based upon work supported by the former Mining and Geological Survey of Hungary. István Waltner's contribution was supported by Project no. FK 124803, implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the FK_17 funding scheme.

References

Abdelaziz, M.O., Nehad, D., Adel, H.E., Salah, E., Mayadah, W F., Aitazaz, A.F., and *Zaher, M.Y.,* 2022: Effects of Irrigation Method and Water Flow Rate on Irrigation. *Agricult. J. 12(8),*1164. https://doi.org/10.3390/agriculture12081164

Al-Kayssi, A.A.-K. ,1990: Influence of soil moisture content on soil temperature and heat storage under greenhouse conditions. *J. Agricult. Engin. Res. 45*, 241–252. https://doi.org/10.1016/S0021-8634(05)80076-9

Angel, S., Sheppard, S., and *Civci, D.,* 2005: The Dynamics of Global Urban Expansion. Washington D.C., Transport and Urban Development Department: The World Bank Report. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.309.2715&rep=rep1&type=pdf

Bai, Y., 2009: Distribution of Soil Temperature Regimes and Climate Change in the Mojave Desert Region. University of California Riverside: Electronic Theses and Dissertations.

Bowler, D., Buyung-Ali, L., Knight, T., and *Pullin, A.,* 2010: Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Lands. Urban Plan. J. 11*, S147. https://doi.org/10.1016/j.landurbplan.2010.05.006

Brady, N., and *Weil, R.,* 2013: Elementos da natureza e propriedades dos solos (Elements of nature and soil properties: Bookman.

Brown, R. and *Gillespie, T.,* 1995: Microclimatic landscape design: creating thermal comfort and energy effciency. Wiley, Hoboken: John Wiley and Sons.

Burgess, J., Harrison, C., and *Limb, M.,* 1988: People, parks and the urban green: a study of popular meanings and values for open spaces in the city. *Urban Stud. J. 25*(6), 455–473. https://doi.org/10.1080/00420988820080631

Chai, W., Wang, G., Li, Y., and *Hu, H.,* 2008: Response of soil moisture under different vegetation coverage to precipitation in the headwaters of the Yangtze River. *J. Glaciol. Geocryol. 30*, 329–337.

Conway, H., 2000: Parks and people: the social functions. In: Woudstra. The Regeneration of Public Parks. https://doi.org/10.4324/9780203857540

Davies-Colley, R., Payne, G., and *Van Elswijk, M.,* 2000: Microclimate gradients across a forest edge. *New Zealand J. Ecol. 24*(2), 111–121. http://www.jstor.org/stable/24054666

Demuzere, M., Orru, K., Heidrich, O., Okazabal, E., Geneletti, D., Orru, H., Bhave,AG., Mittal, N., Feliu, E., Faehnle, M., 2014: Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *J. Environ. Manage. 146*, 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025

Diniz, J., Carneiro, R., Alvino, F., Sousa, E., and *Sousa, J.,* 2013a: Avaliação do comportamento térmico diário do solo de Campina Grande-PB (Evaluation of the daily thermal behavior of the soil of Campina Grande-PB: *Ravistas Agropecuária Científica no Semiárido (Scientific Agriculture in the Semi-arid Region Journal), 9*, 55–60. https://doi.org/10.30969/acsa.v9i2.372

Erell, E., Pearlmutter, D., and *Williamson, T.,* 2011: Urban Microclimate: Designing the Spaces between Buildings. Earthscan. London. https://doi.org/10.4324/9781849775397

Fiebrich, C. and *Crawford, K.,* 2001: The Impact of Unique Meteorological Phenomena Detected by the Oklahoma Mesonet and ARS Micronet on Automated Quality Control. *Bull. Amer. Meteorol. Soc. 82*, 2173–2188. https://doi.org/10.1175/1520-0477(2001)082<2173:TIOUMP>2.3.CO;2

Gehl, J. and *Gemzoe, L.,* 2001: New City Spaces. The Danish Architectural Press.

González Rouco, J., Von Storch, H., and *Zorita, E.,* 2003: Deep soil temperature as proxy for surface air-temperature in a coupled model simulation of the last thousand years. *Geophys. Res. Lett. J., 30*(21). https://doi.org/10.1029/2003GL018264

Grahn, P., 1985: Man's Needs for Urban Parks, Greenery and Recreation. Institute for Landscape Planning. Alnarp: Swedish Agricultural University.

Honjo, T., 2009: Thermal comfort in outdoor environment. *Glob. Environ. Res. J. 13*, 43–47.

Hu, Q. and *Feng, S.,* 2004: A Role of the Soil Enthalpy in Land Memory. *Amer. Meteorol. Soc. J., 17*, 3633–3643. https://doi.org/10.1175/1520-0442(2004)017<3633:AROTSE>2.0.CO;2

Jacobs, A., Heusinkveld, B., and *Holtslag, A.,* 2011: Long-term record andanalysis of soil temperatures and soil heat fluxes in a grassland area, The Netherlands. *Agric. Forest Meteorol., 151*(7), 774–780. https://doi.org/10.1016/j.agrformet.2011.01.002

Javier, L.-P., Manuel, P., Carlos, L.-F., and *Susanne, S.,* 2018: How do Soil Moisture and Vegetation Covers Influence Soil Temperature in Drylands of Mediterranean Regions? *Water J. 10*(2), 1747. https://doi.org/10.3390/w10121747

Kalnay, E. and *Cai, M.* (2003: Impact of urbanization and land-use change. *Nature 423*(6939), 528–531. https://doi.org/10.1038/nature01675

Kong, F., Yan, W., Zheng, G., and *Yin, H.,* 2016: Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation. *Agric. Forest Meteorol. 217*, 22–34. https://doi.org/10.1016/j.agrformet.2015.11.005

Konijnendijk, C., Annerstedt, M., Nielsen, A., and *Maruthaveeran, S.,* 2013: Benefits of Urban Parks – A systematic review. A Report for IFPRA.

Li, Y., Kang, W., Han, Y., and *Song, Y.,* 2018: Spatial and temporal patterns of microclimates at an urban forest edge and their management implications. *Environ. Monitor. Assess. 190*(2), 93. https://doi.org/10.1007/s10661-017-6430-4

Loures, L., Santos, R., and *Panagopoulos, T.,* 2007: Urban Parks and Sustainable City Planning-The Case of Portimão, Portugal. *WSEAS Transact. Environ. Develop. J. 3*.

Mahmoud, A., 2011: Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. *Build. Environ. J. 46* (12), 2641–2656. https://doi.org/10.1016/j.buildenv.2011.06.025

Oké, T., 1981: Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Int. J. Climatol. 1*, 237–254. https://doi.org/10.1002/joc.3370010304

Prevedello, C., 2010: Energia térmica do solo (Soil thermal energy). Sociedade Brasileira de Ciência do Solo (Brazilian Society of Soil Sciences).

Stępniewska, M., 2021: The capacity of urban parks for providing regulating and cultural ecosystem services versus their social perception. *Land Use Policy J. 111*, 105778. https://doi.org/10.1016/j.landusepol.2021.105778

Steward, I. and *Oké, T.,* 2012: Local climate zones for urban temperature studies. *Bull. Amer.Meteorol. Soc. 93*, 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Susca, T., Gaffin, S., and *Dell'Osso, G.,* 2011: Positive effects of vegetation: Urban Heat Island and green roofs. *Environ. Pollut. J. 159*, 2119–2126. https://doi.org/10.1016/j.envpol.2011.03.007

Thorsson, S., Lindqvist, M., and *Lindqvist, S.,* 2004: Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg. *Int. J. Biometeorol. 48*(3), 149–156. https://doi.org/10.1007/s00484-003-0189-8

United Nations, 2014: Transforming our World: The 2030 Agenda for Sustainable Development.

USEPA, 2017: United States Environmental Protection Agency (), Office of Water: Green Infrastructure in Parks: A Guide to Collaboration, Funding, and Community Engagement.

Venables, W.N., Smith, D.M. and the R Core Team, 2023: An Introduction to R – User manual, p. 105. https://cran.r-project.org/doc/manuals/r-release/R-intro.pdf

Vogel, M., Zscheischler, J., and *Senevirante, S.,* 2018: Varying soil moisture–atmosphere feedbacks explain divergent temperature extremes and precipitation projections in central Europe. *Earth Syst. Dynam. J., 9*, 1107–1125. https://doi.org/10.5194/esd-9-1107-2018

Zhang, Y., Chen, W., Smith, S., Riseborough, D., and *Cihlar, J.,* 2005: Soil temperature in Canada during the twentieth century: Complex responses to atmospheric climate change. *J. Geophys. Res.: Atmospheres, 110*(D3), D03112. https://doi.org/10.1029/2004JD004910