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Soil temperature dynamics in the forest shelterbelt and in the field

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Abstract: This study compares soil temperature data collected between 2019 and 2022 in Hrušky, South Moravia, Czech Republic. Soil temperature was measured at five depths (5, 10, 20, 50, 100 cm) in the forest shelterbelt (windbreak) and at three distances from it to investigate the impact of the shelterbelt on the climatic conditions of adjacent field plots. In particular, monthly averages, calculated from average daily temperatures, were employed to characterise the temperature course. These are calculated as averages of measured temperatures at 15-minute intervals. Absolute and relative differences and, where appropriate, base indices, were calculated to facilitate the comparison of individual measurement points (sites) and soil depths. The soil temperature values and their dynamics during the year differ between the measurement point in the forest shelterbelt (90-0) and those in the field. Additionally, the field measurement points exhibit some degree of variation, with the more distant field measurement point (180-90) displaying distinct characteristics from the closer field measurement points (90-45, 90-90). During the winter months (December, January, February), the temperature increases with soil depth, being highest within the windbreak. In spring (February and March), the temperature at different soil depths starts to equalise; however, in April, the temperature decreases with soil depth. Throughout the summer, the measurement station within the windbreak has lower temperatures than in the field, where the soil shows higher temperatures at all depths compared to the windbreak measurement station. In August, the temperature differences in depth begin to equalise again. In September, the temperature trend reverses, and from October, the temperatures increase with soil depth, especially in the lower layers of the soil. The temperature trend in November has a more or less winter character. Soil temperatures in the forest shelterbelt are lower in the summer months and higher in the winter months than in the field. The protective effect of the windbreak is more pronounced at measurement stations closer to the belt, as the temperatures at the farthest field measurement station are higher in summer and lower in winter compared to the closer field measurement stations.

Keywords: agriculture landscape; field microclimate; windbreaks

Soil temperature plays an important role in shaping the local climate, influencing the growth and development of soil organisms and co-determining soil fertility. Soil temperature monitoring is not as frequent as, for example, air temperature monitoring, but it is necessary for a number of agronomic and phenological purposes (Krčmářová et al. 2013), as well as for forestry purposes. Soil temperature data are important for the study of root systems and processes associated with plant growth and

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development (Janík 2005; Krčmářová et al. 2014). In agriculture, soil temperature is a very important agroclimatic factor that influences sowing time, germination and overwintering of plants, as well as water and air regimes, crop phenology and edaphon activity (Středová et al. 2014). It can also influence the activity of various pathogenic organisms and pests (Krčmářová et al. 2014). In addition, soil temperature is an important pedogenetic factor, conditioning the process of mineral weathering, organic matter transformation and carbon decomposition (Lehnert 2014; Středová et al. 2014). It affects the soil edaphon, thus becoming an important factor in soil fertility (Pokladníková, Rožnovský 2007; Středová et al. 2014). Many authors agree that although soil temperature affects virtually all parts of the terrestrial biosphere, its study has not received sufficient attention (Nosek 1972; Bedrna et al. 1989; Možný 1991; Buchan 2001).

The sources of soil heat are solar energy, atmospheric air (heat), decomposition of organic matter (heat release during metabolic processes) and the Earth's internal heat. The main source is solar radiation, 50–80% of which is absorbed by soils and some of which is reflected (Vavříček, Kučera 2017). The absorption of heat by the soil surface is influenced by the position and slope of the land, and soil heating is also influenced by vegetation (Laník, Halada 1960). The consequence of soil warming is partly evaporation and partly heating of the ground layer of the atmosphere (Vavříček, Kučera 2017).

Soil temperature values are also determined by the physical properties of the soil, especially its thermal properties, which are significantly influenced by the soil water content (Středová et al. 2014). The soil remains warmer than the air in the lower layers for a relatively long time until autumn – it acts as a heat accumulator – and in spring, it is cooler than the air, therefore slowing down the awakening and growth of vegetation and early germination (Laník, Halada 1960; Vavříček, Kučera 2017). Soil temperature influences plant water uptake, as it determines both the absorption capacity of the roots and the magnitude of the resistance to water movement through the soil and its entry into the roots. Plants can obtain water more readily from warm soils than from cold ones (Larcher 1988).

External factors affecting the soil temperature regime are the intensity and balance of radiation, the angle of incidence of the sun's rays on the soil surface, altitude (and the associated duration and depth of snow cover and the climatic regime of the area) and evapotranspiration. Thus, the soil temperature regime is the result of radiation and energy balance (Středová et al. 2014; Vavříček, Kučera 2017).

The internal factors are the specific heat and thermal conductivity of the soil, as well as its colour. Dark soils are generally warmer and absorb more heat (have lower albedo). Moist soils conduct heat from the surface layer to the subsoil better than dry soils; loose soils heat more strongly in the surface layer but do not share the heat with the subsoil (Laník, Halada 1960). The wetter the soil, the less it heats (Haslbach, Vaculík 1980). Moist soils heat up more slowly but warm up to a greater depth and act as a heat reservoir (Uhlíř 1961). The soil water movement is also important in conducting heat from the surface to the depth of the soil, and vice versa. In loose soil, heat is poorly transferred from the surface to the depth during the day and from below to the surface at night, compared to solid soil. The changes in soil temperature with depth are greater in loose soil than in solid soil (Uhrecký 1962). In the daytime, heat is transferred to the subsoil in well-conducting soils so that the surface does not heat up as much. At night, it is brought to the surface and prevents the soil from cooling very much, which is particularly dangerous for plants at the beginning of the growing season (Uhlíř 1961).

Vegetation is an important factor influencing the soil temperature regime. Vegetation, especially tree-like vegetation, reduces the availability of radiation to the land surface. However, it also reduces the radiation of stored heat in the soil and overall reduces the extremes of microclimatic conditions, whereas on bare soil, both the uptake and radiation of heat energy are more intense (Vavříček, Kučera 2017). Green et al. (1984) state that vegetation acts as a thermal insulator and significantly influences the soil temperature regime. Therefore, soil under dense vegetation is cooler in summer and warmer in winter. Vegetation therefore acts as a thermal insulator and significantly influences the soil temperature regime. Outside the growing season, the soil in the forest geobiocenosis is protected from freezing by a layer of litter, which can have a significant effect on the depth of soil freezing, depending on the tree species. (Jackson et al. 2005;

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Kupka, Podrázský 2010). In addition to the direct influence of vegetation on the radiation and energy balance of the soil surface described above, vegetation also influences soil temperature indirectly. Lower wind speeds reduce the loss of latent heat from the soil surface. Therefore, vegetation creates a specific microclimate characterised by its own moisture and temperature regime (Jarvis 1985; Cellier et al. 1996; Středová et al. 2011). The action of forest shelterbelts (windbreaks) is usually of a complex nature related to airflow modification. Therefore, other microclimate parameters such as air temperature and humidity, evapotranspiration, soil temperature and others are also affected (Forman, Godron 1993; Litschmann, Rožnovský 2004; Blažek 2013). All of this depends on the structure, orientation and permeability of the forest shelterbelt, the initial wind speed in the open landscape and the angle at which the air hits the windbreak (Sus 1950). The time of day at which the measurement of microclimatic parameters is carried out is also important. (Brandle et al. 2004). Moreover, according to Cleugh and Hughes (2002), the effects of a forest shelterbelt on the microclimate in the protected area are much shorter in distance than its effect on reducing wind speed. The effect of highly porous (permeable) windbreaks on microclimate is then negligible.

The soil temperature conditions are changed by the windbreaks mainly due to the reduction of wind speed in the area protected by them. The average daily temperature is increased by 1–3 °C in the protected area, while non-permeable windbreaks increase the soil temperature by up to 6 °C (Podhrázská, Dufková 2005). Furthermore, the higher the air temperature, the lower the effect of forest shelterbelts (Deng et al. 2011). The increase in temperature can result in faster stand growth, especially for plants requiring higher heat accumulation for germination (Drew 1982). On the other hand, temperatures above the optimum value for plant development can cause water stress if the plant is unable to adapt to higher moisture requirements (Brandle et al. 2004). Conversely, when a forest shelterbelt shades the land, soil temperatures are reduced. This is dependent on the location of the forest shelterbelt, its height, time of day, and the angle of sunlight (Caborn 1957; Brandle et al. 2004).

The aim of this study was to investigate soil temperature patterns in the forest shelterbelt and at different distances from it. This was in the protected area at a distance of 5 to 10 forest belt heights. In order to determine the depth temperature pattern, five temperature sensors were used at each measurement point and soil temperature was measured to a depth of 1 m. The main research objective was to answer the question of what the differences in the dynamics of soil field temperatures were at distances closer to the forest shelterbelt and at distances further away.

MATERIAL AND METHODS

The selected site is located in the cadastral area of the municipality of Hrušky, situated in the southernmost part of the South Moravian Region less than 8 km east of the town of Břeclav, in the Czech Republic (Figure 1). It is an intensively farmed landscape characterised by large fields alternating with strips of forest shelterbelts (windbreaks). The area is located at an altitude of about 175 m a.s.l., with a slope of up to 3°. The average annual rainfall is 538 mm, and the average annual temperature is 9.5 °C. In terms of soil texture, there are loamy soils. The soil substrate is made up of loess, and the soil type represented is chernozem (Jandák et al. 2010). The research site is located in the Hustopeče biogeographical region (Culek et al. 2013), the group of geobiocene types is *Ligustri-querceta* (Buček, Lacina 1999).

The site of the so-called 'Příčný výhon', where two windbreaks meet orthogonally, was chosen for the research. The maximum wind reduction is already achieved at a distance of 4–5 times the height of the windbreak; there is also the highest reduction in evaporation and, at the same time, the greatest increase in soil moisture and temperature (Forman, Godron 1993; Trnka 2003). The effects on the microclimate on the adjacent plot decrease sharply

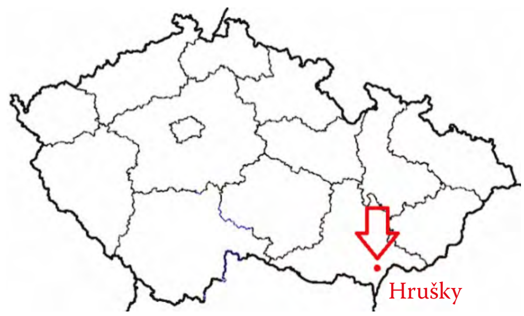

Figure 1. Location of the research plot

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from a distance of 10 plant heights (Trnka 2003) to 12 plant heights (Forman, Godron 1993, Campi et al. 2009), and the wind speed returns to the original values at a distance of 28 times the height (Forman, Godron 1993). Thus, the measured plot was placed in the first 180 m (up to 10 times the height of the windbreak) of the windbreak length and in the field on its leeward side. Measurement points by probes with soil temperature sensors were established directly in the windbreak, and at three points in the adjacent field at different distances from the two windbreaks; the measurement started in June 2018 (Figure 2).

The forest shelterbelt (windbreak), whose climatic effect is assessed in this study, is ideally positioned in relation to the prevailing southeasterly winds. First, the species and spatial structure of the windbreaks were assessed, resulting in the evaluation of the windbreaks in this area as a semi-permeable windbreak with an age of 72 years.

A semi-permeable windbreak consists of multiple layers of trees and shrub layers. The tree canopy has lower cover, or the shrub layer is not very dense (developed to a lesser extent), resulting in optimal permeability of 40–50% compared to a non-permeable type (Podhrázská et al. 2008). The species structure of the stand is predominantly composed of specimens of pedunculate oak (*Quercus robur* L.), Turkey oak (*Quercus cerris* L.) and field elm (*Ulmus minor* L.), with the last specimens of black poplar (*Populus nigra* L.) in the centre of the line and the non-native boxelder maple (*Negundo aceroides* L.) also abundant in the understorey. The average width of the windbreak reaches 20 m and the height of the main storey is around 18 m. The adjacent field land is under conventional farming, with traditional agricultural crops such as wheat (2018, 2022), maize (2019, 2020), and sunflowers (2021).

Platinum resistive sensors Pt100 (Amet company from Velké Bílovice, Czech Republic) were used to measure soil temperature. The sensors were installed at depths of 5, 10, 20, 50, and 100 cm according to the methodology of the Czech Hydrometeorological Institute (Středová et al. 2016). Soil temperature was measured at 15-minute intervals and downloaded in the 'ALA connect' program (Version 1.10, 2015).

In particular, the characterisation of the temperature course was based on the calculation of monthly averages from the average daily temperatures. These are calculated as the mean of the temperatures recorded at 15-minute intervals. In order to facilitate comparison of individual measurement points and

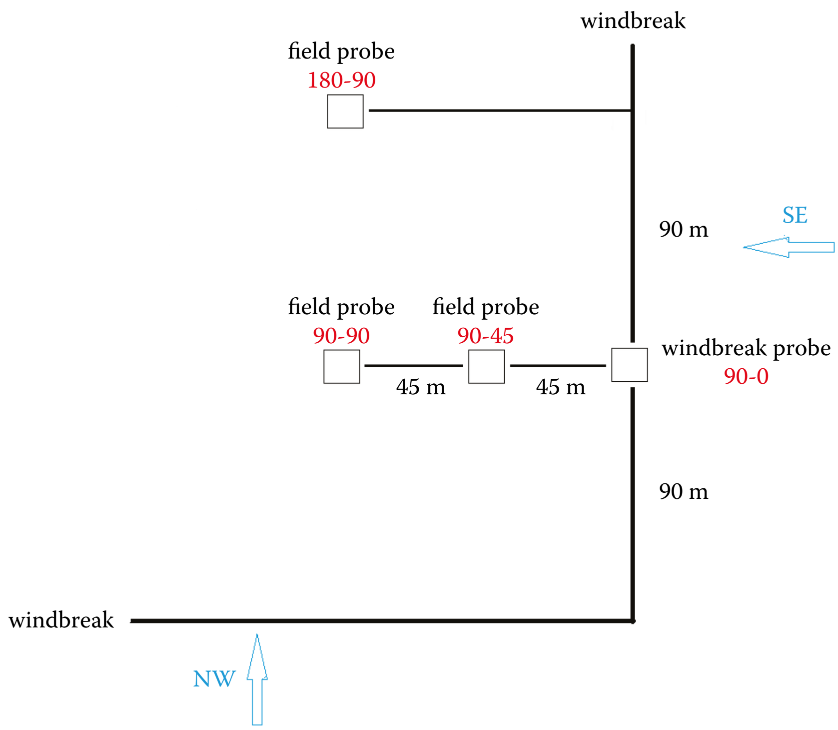

Figure 2. Diagram of the measurement points

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soil depths, absolute and relative differences were calculated, as were base indices where appropriate. The statistical similarity of the monthly averages was determined through the application of a *t*-test, which was employed to test for the similarity of means. This was preceded by an *F*-test to test the similarity of the variances. The statistical similarity of the relative differences of the individual monthly averages was determined by means of a *t*-test.

RESULTS AND DISCUSSION

The recorded soil temperature at 15-minute intervals by soil depth and measurement sites is documented graphically in Figure 2. The highest average daily soil temperature was recorded on June 14, 2019, in the topmost soil layer at the furthest field measurement point (180-90) at 32.09 °C. The lowest daily average soil temperature was recorded there on February 14, 2021, at –1.78 °C. The highest temperature ever recorded was 41.6 °C and the lowest temperature was –3.5 °C, again in the same layer and at the same measurement point.

The dynamics of soil temperatures in each year at each measurement point and at each soil depth is shown using monthly averages (Figure 3).

The course of soil temperatures between 2020 and 2022 at each measurement point is shown on the basis of monthly averages, for each depth separately (Figure 4), then as temperature differences between depths (Figure 5) and finally as temperature differences between months (Figure 6).

Summary of results. The upper layers (T1 at 5 cm, T2 at 10 cm, T3 at 20 cm) were further taken as one layer (denoted 'HV' – upper layer) and the lower layers (T4 at 50 cm, T5 at 100 cm) as the second layer (denoted 'DV' – lower layer) and the temperatures for these layers were calculated as averages of the temperatures of the respective depths. The upper layer corresponds to the main root layer and, on the field measurement points, corresponds to the more or less ploughed part of the soil. From the field measurement points closer to the windbreak (90-45, 90-90), the average values (labelled 90-to-90) were calculated. This is to make the results more transparent. This was made possible by the proximity of many of the 90-45 measurement point values to the 90-90 measurement point. The windbreak measurement point is therefore further compared with the closer (90-to-90) and more distant field measurement point (180-90).

The lower layer of the windbreak measurement point (90-0) shows the lowest temperatures in the spring (April, May) and summer (June, July, August) months, and the highest temperatures in the winter months (December, January, February). The reversal occurs in spring in March and in autumn in September–October. November is the transition to the winter temperature course (the temperature of the lower layer of the 90-0 measurement point equals the temperature of the lower layer of the more distant 180-90 field measurement point).

At the same time, the upper layer of the windbreak (90-0) is warmer in the winter months (December, January, February) than the upper layers at the field measurement points, and in January the far field measurement point (180-90) is colder than the closer field measurement point (90-to-90). From March to September, the upper layer of the windbreak is cooler than the upper layers of both field measurement points. In October, temperatures reverse, and the temperature of the upper windbreak layer is higher than the field measurement points.

In March the temperatures at the field measurement points rise the further the measurement point is from the windbreak. In April, the temperatures at the field measurement points are balanced and the closer measurement point (90-to-90) shows slightly higher temperatures for both the upper and lower layers. There is a similar distribution of temperatures (albeit slightly higher) in May. From June to September, both upper layer and lower layer temperatures increase away from the windbreak. In summer, the differences between the measurement points are smallest, while in September they are large. In October, the lower layer temperatures remain rising towards the field, but the upper layer is already warmest in the windbreak, albeit by a small difference. In November, the lower layer is also warmer in the windbreak than at the field measurement points. The field measurement points have an even soil temperature. In December, the upper layer shows a decreasing temperature from the windbreak to the field, but the lower layer is also at a higher temperature in the windbreak, but the field measurement points are at an even temperature.

The curves of monthly temperature averages are shown in Figure 7 using the base indices (increments). The flattest curve is exhibited by the lower layer temperatures in the windbreak (90-0) with

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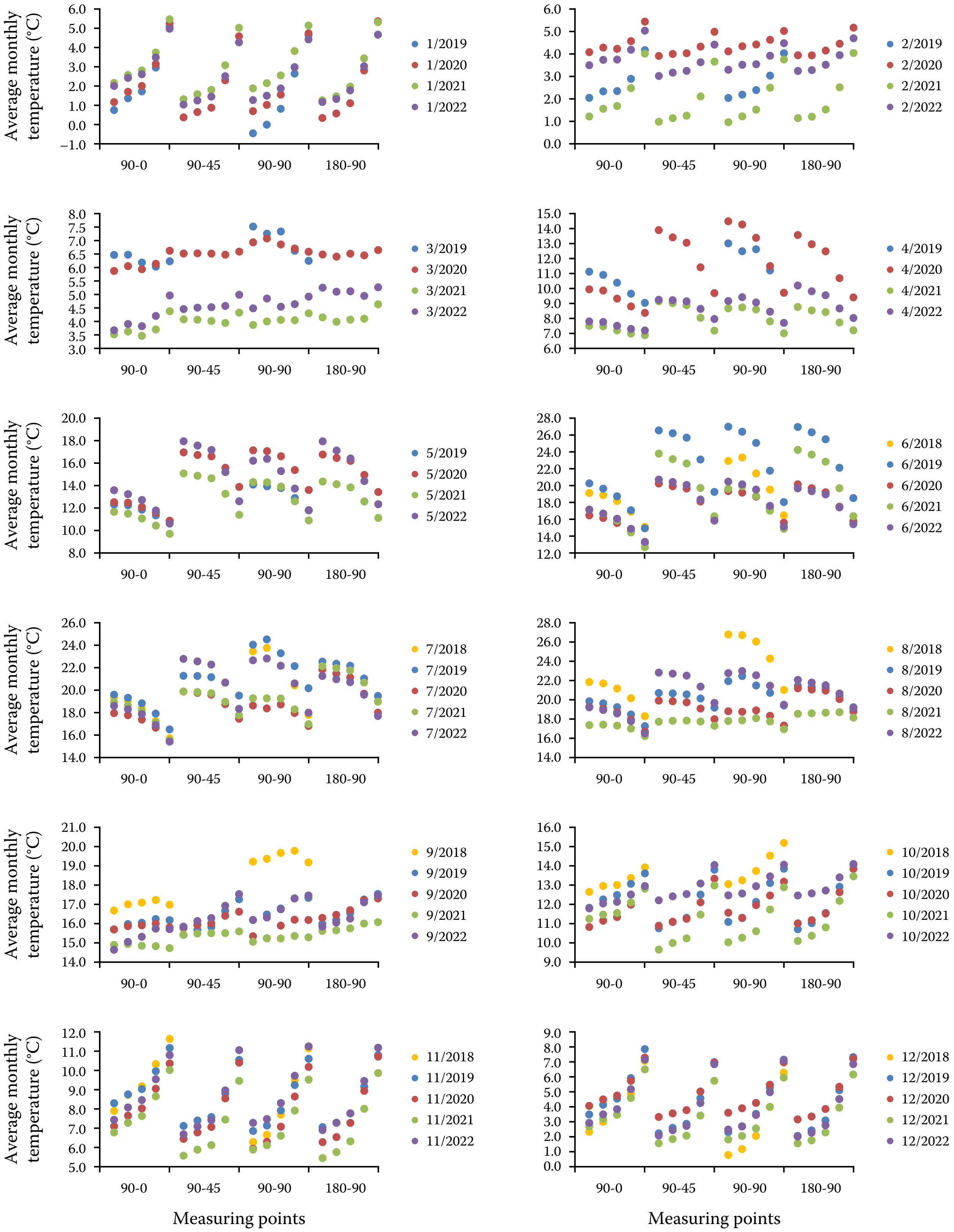

Figure 3. The course of average monthly temperatures as a function of soil depth

The chart is arranged in twelve sections by month, these are divided into sections by measurement point; soil depths are expressed as a sequence of temperature values from the top layer to the deepest layer

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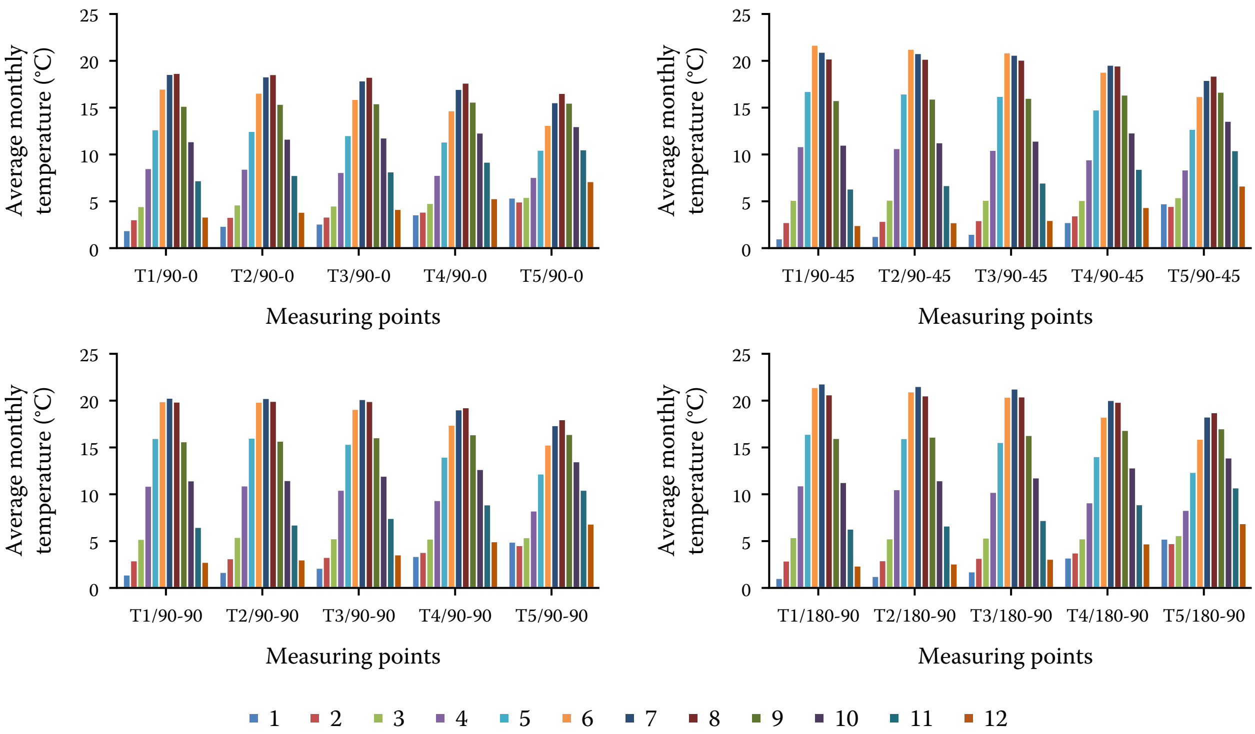

Figure 4. Monthly temperature averages for the period from 2020 to 2022 as a function of soil depth

The chart is arranged in four sections by measurement point, these are divided into sections according to the measured soil depth, months are expressed by colour; T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

a more gradual increase until the peak in August. This is followed by the curves of the lower layers of the field measurement points, which are very similar to identical. The temperature trend at the more distant field measurement point does reach higher values in summer. For the lower layers of all

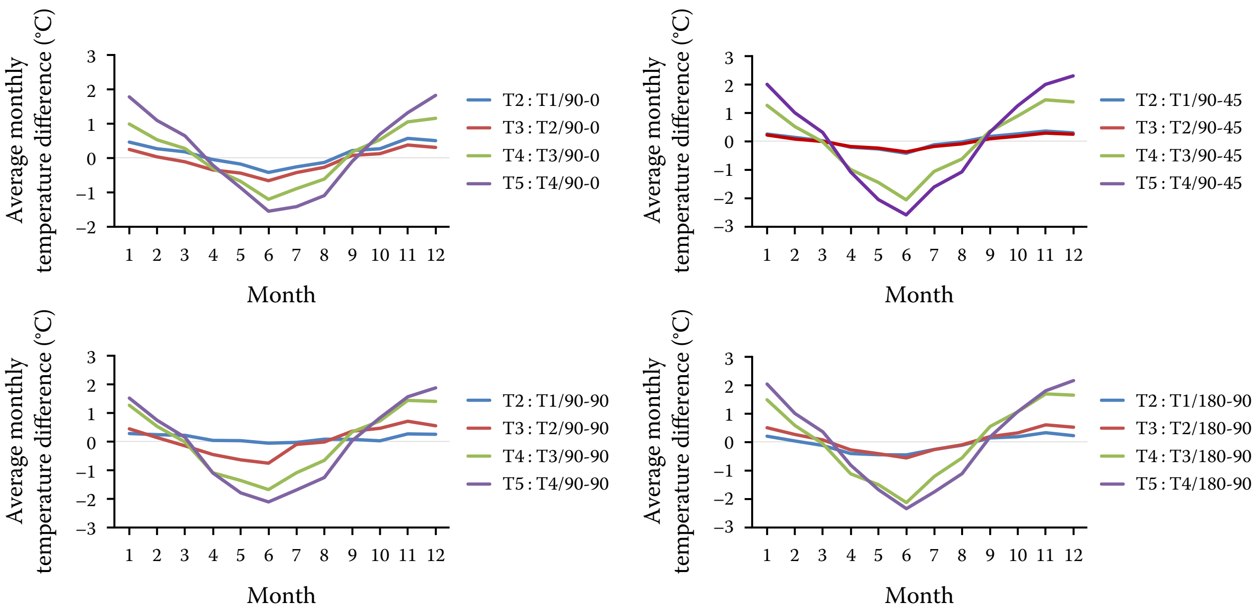

Figure 5. Differences in average monthly soil temperatures from 2020 to 2022 as a function of soil depth

The chart is arranged in four parts by measurement point; the differences between soil depths are expressed in colour; T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

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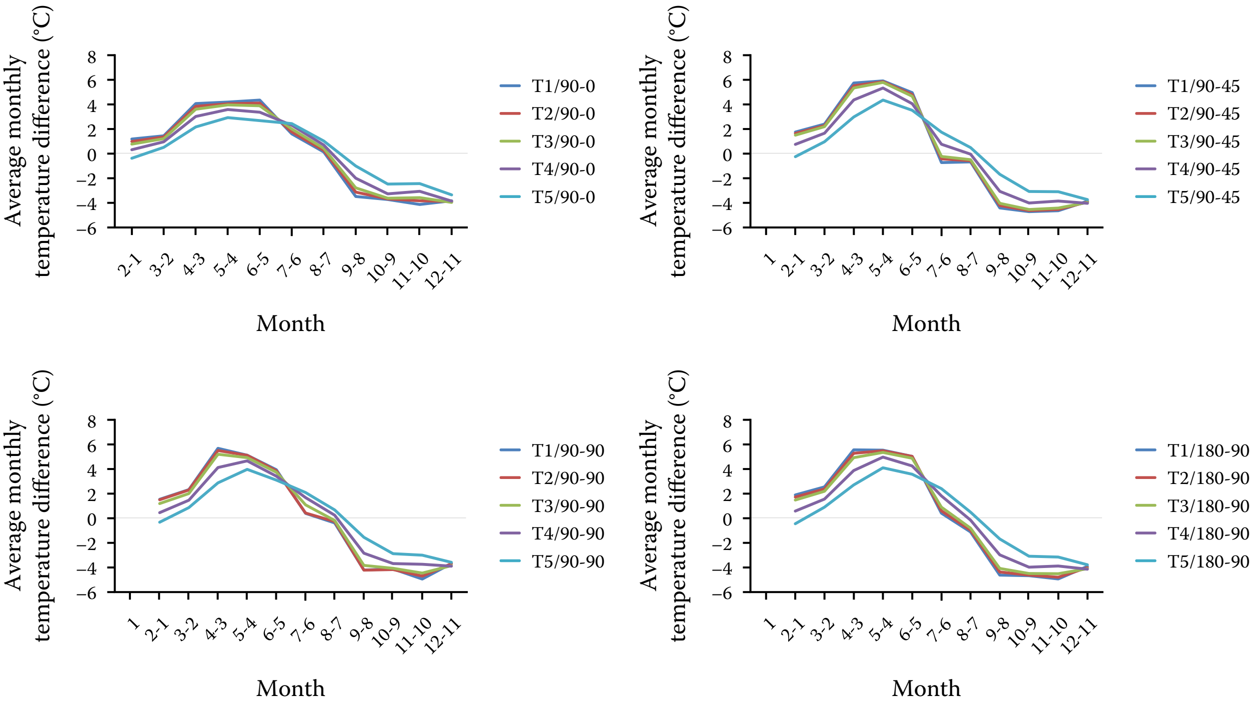

Figure 6. Differences in average monthly soil temperatures for the period 2020 to 2022 compared to neighbouring months

The chart is arranged in four parts by measurement point; soil depths are expressed in colour; T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

measurement points, there is not yet a temperature rise in February, unlike the upper layers.

The upper layer in the windbreak shows slightly higher basal increments from the beginning of the year until August compared to the lower layers of the field measurement points, but it is close to them. From September to December, the basal increments are essentially the same. The upper soil layers of the field measurement points have significantly higher basal increments than the lower layers of all measurement points and also than the upper layer in the windbreak. Basal increments in November and December are the same in all measurement points in both soil layers.

(A) absolute basis indices (B) basis indices

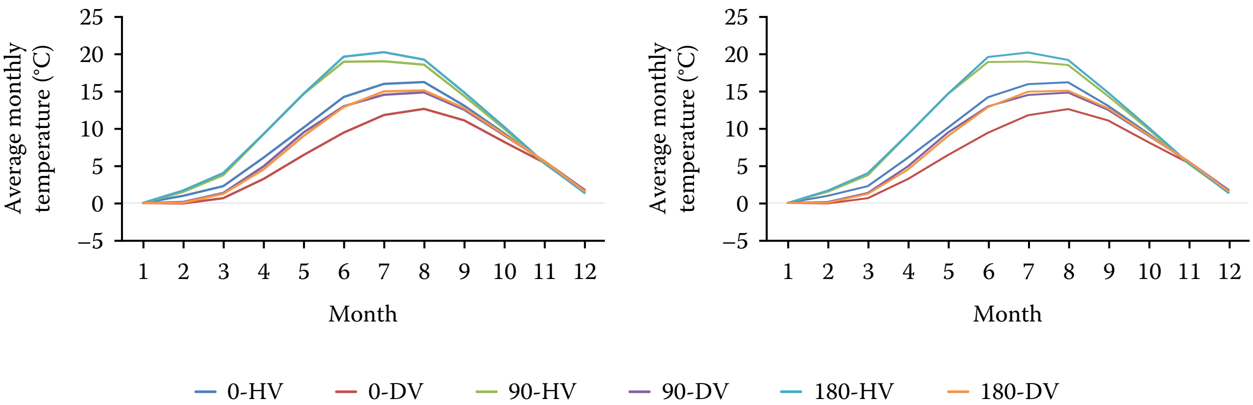

Figure 7. The course of the basis indices (the base is January)

0 – windbreak measurement point (90-0); 90 – field measurement point 90-to-90 (average of field measurement points 90-45 and 90-90); 180 – field measurement point 180-90; HV – upper layer (average of T1, T2, T3); DV – lower layer (average of T4, T5); T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

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Three types of courses can be observed. First, a flatter one, represented by the lower layer of the windbreak measurement point (90-0) with a flatter peak shifted towards the end of summer. The highest basal increment is in August. Then follows a course characterised by higher basal increments with a steeper increase from March to June and a peak into August followed by a break in September. The highest basal increments are again in August. This includes the lower layers of the field measurement points and the upper layer in the windbreak. The upper soil layers of the field measurement points represent a third type of course – with the highest basal increments and a steep increase from March to June, but with a bounded peak in the summer months from June to August, when the June basal increment equals the August increment and there is a slight peak in July. August is followed by a steep descent to a value in November that is equal to all courses.

The course of the monthly average temperatures for the period 2020–2022 is shown in Figure 8 and Table 1. It can be observed that the more distant field measurement point (180-90) shows the lowest temperatures in the upper soil layer in the winter months and the highest in the summer months. A very similar course and temperatures were measured in the upper layers of the closer field measurement points (90-45 and 90-90), with the summer peak being insignificant. The upper soil layer in the windbreak (90-0) is the warmest in winter and autumn months, whereas from April to August it is significantly cooler than the upper layers of the field measurement points. In March and September, the temperature is also lower than these field measurement points, but less than in summer.

The temperature course of the lower soil layers is similar to that of the upper layers. However, there are smaller differences between months and a smaller annual range. This is true for all measurement points, but the measurement point in the windbreak shows the smallest differences. Upper layer temperatures peak at values over 20 °C, starting at 1.2 °C to 2.2 °C in winter, lower layer temperatures just touch the 20 °C threshold in summer (18.7, 19.1 °C), and fall just below 5 °C in winter (3.8 °C for closer field measurement points, 4.1 °C for more distant field measurement points).

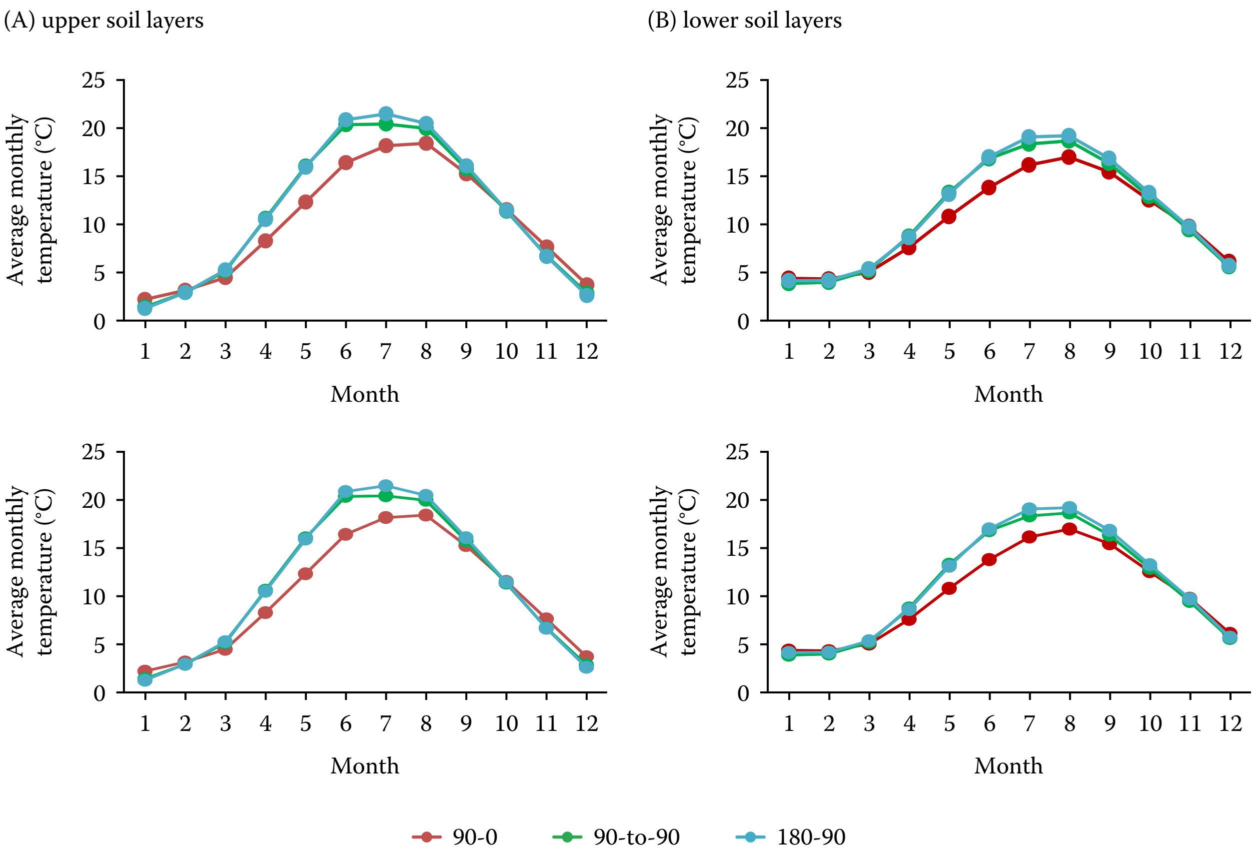

Figure 8. Temperature course of monthly averages of upper and lower soil layers

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Table 1. Average monthly temperatures (°C) in 2020–2022

Month	90-0		90-to-90		180-90	
	HV	DV	HV	DV	HV	DV
1	2.2	4.3	1.4	3.8	1.2	4.1
2	3.1	4.3	2.9	3.9	2.9	4.1
3	4.4	5.0	5.1	5.2	5.2	5.3
4	8.2	7.6	10.6	8.7	10.5	8.6
5	12.3	10.8	16.0	13.3	15.9	13.1
6	16.4	13.8	20.3	16.8	20.9	17.0
7	18.1	16.2	20.4	18.4	21.5	19.1
8	18.4	17.0	19.9	18.7	20.5	19.2
9	15.2	15.4	15.7	16.3	16.0	16.8
10	11.5	12.5	11.3	12.9	11.4	13.3
11	7.6	9.7	6.7	9.4	6.6	9.7
12	3.7	6.1	2.8	5.6	2.5	5.7

HV – upper layer, i.e. topsoil (average of T1, T2, T3); DV – lower layer, i.e. bottomsoil (average of T4, T5); T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

Determining the similarity of temperature courses by statistical testing. Annual temperature averages, calculated from monthly averages, are very similar at all measurement points and depths. On the other hand, at those depths where summer temperatures are higher, winter temperatures are lower, and so the averages are similar (Table 2). For example, the annual averages at the windbreak range from 10.05 °C to 10.31 °C; at the more distant field measurement point (180-90) they range from 11.21 °C to 11.37 °C. Here the variance shows greater differences both between depth layers within a measurement point and between measurement points. For example, annual averages at the windbreak show a variance of 18.48 to 39.39; at the more distant field measurement point (180-90) the variance is 27.98 to 60.70.

The values of the *P*-statistic of the *F*-test are then usually many times more than the level of statistical significance (0.05) for all the compared temperature (depth and measurement point) profiles (Table 3). Only the temperature of the deepest soil layer (T5 at 100 cm) in the windbreak (90-0) compared with the temperature at the field measurement points of layers T1 (5 cm), T2 (10 cm) and partly also T3 (20 cm) approach the level of statistical significance. The values of the *P*-statistic of the *t*-test are even larger and do not approach the level of statistical significance in any of the cases compared. The Student's *t*-test compares the means of the selections and these are very similar.

The results show that the lower layer of the windbreak measurement point (90-0) shows the lowest values in the spring and summer months (April, May, June, July, August) and the highest temperatures in the winter months (December, January, February). The vegetation of the windbreak, which maintains a microclimate throughout the year, causes the soil to be cooler in summer and warmer in winter. This fact is noted by Green et al. (1984), who liken the action of sufficiently dense vegetation to a thermal insulator, significantly influencing the soil temperature regime. If the soil is bared for some part of the year, as is common in crop fields, the larger temperature amplitudes, usually more typical of vegetation surfaces, take place at the soil surface itself and the whole soil horizon is subject to temperature changes more rapidly. Consequently, temperature differences of soil are smaller in windbreak than in field measurement points.

The maximum daily soil temperature in the summer of 2018 and 2019 was above 30 °C, reaching up to 38 °C around noon. Maximum survival temperature (with long exposure) for plants is commonly approximately 55 °C, but respiration generally exceeds photosynthesis at approximately 50 °C (Spurr, Barnes 1973). The most common deleterious effects of high temperatures are the excessive loss of moisture and the stimulation of excessive respiration rates. Because of the low albedo and low conductivity of many soils, surface temperatures frequently become very high,

https://doi.org/10.17221/52/2024-JFS

Table 2. Statistical variables

Measuring points	T1	T2	T3	T4	T5
			(°C)		
90-0					
Average	10.0	10.2	10.1	10.1	10.3
Average deviation	5.4	5.2	5.0	4.5	3.6
Maximum	18.6	18.4	18.2	17.5	16.4
Minimum	1.8	2.2	2.5	3.5	4.8
Standard deviation	6.0	5.8	5.6	5.0	4.1
90-45					
Average	11.1	11.2	11.2	11.1	11.2
Average deviation	6.5	6.4	6.3	5.6	4.6
Maximum	21.6	21.2	20.8	19.4	18.3
Minimum	0.9	1.1	1.4	2.6	4.3
Standard deviation	7.4	7.2	7.1	6.2	5.1
90-90					
Average	10.9	11.1	11.1	11.1	11.0
Average deviation	6.1	6.0	5.9	5.3	4.4
Maximum	20.2	20.1	20.0	19.1	17.9
Minimum	1.3	1.5	2.0	3.3	4.4
Standard deviation	6.9	6.8	6.5	5.8	4.8
180-90					
Average	11.2	11.2	11.2	11.3	11.3
Average deviation	6.6	6.5	6.3	5.6	4.6
Maximum	21.7	21.5	21.2	20.0	18.7
Minimum	0.9	1.1	1.6	3.1	4.5
Standard deviation	7.5	7.3	7.1	6.1	5.1

T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

and plants may be damaged where they contact the soil surface (Kimmins 1987). The high soil temperature also affects soil organisms, whose optimal temperature ranges between 25–30 °C. Additionally, it is true that most soil animals require temperatures above 20 °C, and the biochemical activity of the soil increases with rising temperatures (Jandák et al. 2010).

Table 3. Results of statistical tests

Measuring points		90-0		90-to-90		180-90	
		HV	DV	HV	DV	HV	DV
90-0	HV	–	0.438	0.546	0.847	0.465	0.908
	DV	0.951	–	0.172	0.558	0.137	0.508
90-to-90	HV	0.718	0.734	–	0.427	0.899	0.472
	DV	0.681	0.692	0.999	–	0.358	0.939
180-90	HV	0.682	0.695	0.958	0.953	–	0.398
	DV	0.612	0.614	0.928	0.916	0.975	–

Above main diagonal – results of *P*-statistics of *F*-test; below main diagonal – results of *P*-statistics of *t*-test; HV – upper layer (average of T1, T2, T3); DV – lower layer (average of T4, T5); T1, T2, T3, T4, T5 – temperatures at 5, 10, 20, 50, and 100 cm, respectively

https://doi.org/10.17221/52/2024-JFS

The windbreak stand (90-0) also had significantly lower mean monthly soil temperature values than the field plot at all measured depths during the first half of the growing season, i.e. April to July, which is true for all measured summers. The reduction of temperature extremes and amplitude of topsoil temperature values during the year is found in the study of Janík (2005), who follows the dynamics of soil temperatures at different stages of forest development and finds that at a depth of 5 cm, the lowest mean annual soil temperature is reached in a fully-closed stand, while in an open, unforested area, both mean temperature values and annual maxima are higher. At a depth of 20 cm, the differences are not as pronounced, and the mean annual soil temperature was even the same, which was not confirmed by this study. Song et al. (2013) investigated the soil temperature dynamics of grasslands and found that soil temperature increases with decreasing vegetation cover. The reduction of the impact of climate extremes by the positive effect of vegetation cover is also confirmed by works dealing with soil surface or ground layer temperature. For example, Poleno et al. (2011) find lower annual mean soil surface temperatures in forests compared to fields, and Vopravil et al. (2022) confirm at heights of 20–60 cm from the surface a reduction in air temperature of up to 1.1 °C in forested areas compared to agricultural land during the months of April to November.

The effect of a forest shelterbelt on soil temperature (Jarvis 1985; Cellier et al. 1996; Středová et al. 2011) has been demonstrated e.g. that in January, the topsoil of the more distant field measurement point (180-90) is cooler than that of the closer measurement point (90-to-90) and that at this most distant measurement point, both the lowest monthly average temperature and the highest monthly average temperature were also reached in the topsoil, and thus the largest amplitude of values, 20.3 °C, was reached there.

Good thermal absorption and conductivity of the soil are particularly important in the spring period, when it is necessary that the heat is dissipated to the subsoil during the day and brought back to the surface at night, thus preventing a large soil cooling, which is particularly dangerous for plants at the beginning of the growing season (Uhlíř 1961). Soil texture plays an important role in this process; heavier textured soils warm up more slowly during the day, and heat is then accumulated more in the deeper layers and replenished from there at night (Vavříček, Kučera 2017). In the case of field measurement points, temperatures in the soil profile are very even in March, with the upper layers being warmed and the lower soil layer cooling very slowly. This accumulation of heat in the lowest measured layer is evident from September to February, and even in January the temperature difference in this layer compared to the topmost layer is about 3 °C. In contrast, in the windbreak, even in the unleafed state, direct sunlight is blocked, and the depth temperature differences remain greater. It is also possible that soil treatment may be a contributing factor, given that soil compaction occurs in the field as a result of agricultural machinery being driven over it. This could potentially lead to an improvement in its thermal conductivity (Uhlíř 1961).

When comparing soil temperature values in the field and in the windbreak, it is also necessary to consider that the field is subject to agricultural management processes. Whether the field contains freshly sown or already dried mature crops, from April to August in all measured years, the soil in the field heats up earlier and more than in the windbreak, which may not be solely due to the type of vegetation cover. Tillage increases non-productive evaporation from the soil and the soil warms up more quickly (Šnobl et al. 2010). Soil management within agronomic operations can therefore have a significant impact on soil temperature; at the measured site, regular mechanical post-harvest or pre-sowing soil preparation was conducted every year.

Soil freezing, where the expansion of water volume during freezing causes the breakdown of large clods ploughed in the autumn, creates a favourable soil structure, aerates the clods, oxygenates the soil, and leads to the decomposition of undesirable residues in the soil by aerobic microorganisms (Jandák et al. 2010; Šnobl et al. 2010), is an important process. During the measured years, the average daily soil temperature in the field was below freezing for only 7 to 12 days per year. If further warming occurs in future years, it is possible that this natural process, which helps improve the structure and quality of agricultural soils, here may no longer take place.

CONCLUSION

Soil temperature values and their dynamics during the year differ at the measurement points in the forest shelterbelt (90-0) from the field measure-

https://doi.org/10.17221/52/2024-JFS

ment points. At the same time, the field measurement points differ to some extent from each other, with the more distant field measurement point (180-90) being different from the closer field measurement points (90-45, 90-90). However, some soil temperature parameters are more similar at the 90-45 field measurement point than at the 180-90 field measurement point.

At the field measurement points, the soil shows higher temperatures at all depths in comparison to the windbreak measurement point.

The lower soil layer of the windbreak measurement point shows the lowest temperatures in spring and summer months and the highest temperatures in winter months among all soil layers of all measurement points. A reversal occurs in spring in March and in autumn in September to October. The upper soil layer of the windbreak is warmer in the winter months but is cooler than the upper layers at the field measurement points from March to September.

The soil temperature dynamics of the upper soil layer in the windbreak are analogous to those of the lower soil layers at the field measurement points. The period from March to June is characterised by a rise in temperature, with a peak in August, followed by a decline in September. The lowest temperature increase is observed in the lower soil layer of the windbreak, with a peak in August, followed by a gradual decline. The lower layers of all measurement points do not yet show a temperature rise in February, unlike the upper layers of all measurement points. The upper soil layers of the field measurement points measured the highest temperature increases, again from March to June. The temperature peak occurs from June to August, with the highest peak in the first half of summer, followed by the highest negative increments (decreases).

The temperatures and their courses of the lower soil layers differ from the upper soil layers of all measurement points in that there are smaller temperature differences between months and a smaller annual temperature range.

The mean monthly temperature of the lower soil layer at the closest field measurement points is comparable to that of the upper soil layer in the windbreak (exceeding 18 °C). The warmest month lower soil layer temperature in the windbreak reaches 17 °C. In the coldest month, the monthly average upper soil temperature is similar at all measurement points, around 4 °C, with the lowest at the closer field measurement points (3.8 °C).

It can be concluded that the temperatures at the measurement points in the forest shelterbelt (windbreak) show a seasonal variation, with lower temperatures in the summer months and higher temperatures in the winter months compared to the field measurement points. The temperature recorded at the most distant field measurement point is higher in summer and lower in winter than at the nearest field measurement point.

The dependency of soil temperature dynamics on the measurement points of the field plot and the corresponding agricultural crop was not proven. In years with the same crops, different soil temperature data were recorded, indicating that soil temperature is more dependent on climatic conditions than on the species of crop covering the soil. Higher soil temperatures were recorded in years with lower precipitation in the spring months, i.e. in years with less vegetation development.

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