Specifics of soil temperature under winter wheat canopy

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Abstract: The aim of this study was to evaluate the course of soil temperature under the winter wheat canopy and to determine relationships between soil temperature, air temperature and partly soil moisture. In addition, the aim was to describe the dependence by means of regression equations usable for phytopathological prediction models, crop development, and yield models. The measurement of soil temperatures was performed at the experimental field station Žabčice (Europe, the Czech Republic, South Moravia). The soil in the first experimental plot is Gleyic Fluvisol with 49–58% of the content particles measuring < 0.01 mm, in the second experimental plot, the soil is Haplic Chernozem with 31–32% of the content particles measuring < 0.01 mm. The course of soil temperature and its specifics were determined under winter wheat canopy during the main growth season in the course of three years. Automatic soil temperature sensors were positioned at three depths (0.05, 0.10 and 0.20 m under soil surface), air temperature sensor in 0.05 m above soil surface. Results of the correlation analysis showed that the best interrelationships between these two variables were achieved after a 3-hour delay for the soil temperature at 0.05 m, 5-hour delay for 0.10 m, and 8-hour delay for 0.20 m. After the time correction, the determination coefficient reached values from 0.75 to 0.89 for the depth of 0.05 m, 0.61 to 0.82 for the depth of 0.10 m, and 0.33 to 0.70 for the depth of 0.20 m. When using multiple regression with quadratic spacing (modeling hourly soil temperature based on the hourly near surface air temperature and hourly soil moisture in the 0.10–0.40 m profile), the difference between the measured and the model soil temperatures at 0.05 m was −2.16 to 2.37 °C. The regression equation paired with alternative agrometeorological instruments enables relatively accurate modeling of soil temperatures ($R^2 = 0.93$).

Key words: soil temperature, canopy, microclimate, sum of effective temperatures

209

1. Introduction

Air temperature data are more readily available and more easily collected than soil temperature data. However, monitoring of soil temperatures is necessary for a number of agronomic and phenological purposes, for soil respiration quantification, microbial transformations of sulphur and nitrogen (in wheat canopy *Weber and Rennenberg, 1996*), for estimating belowground processes for carbon budgets, evaporation etc. As early as in the 1940s, *Wort (1940)* tested the impact of different temperatures (22–42 °C) on the growth of Marquis spring wheat. Similarly, the effects of rising soil temperature, soil hydrothermal properties, winter wheat growth and yield were studied by *Ju et al. (2010). Franzaring et al. (2010)* conclude that also CO_2 enrichment was responsible for changes of the soil microclimate.

Knowledge concerning soil temperature is inevitable for modeling of some plant growth and development models. Moreover, it is sometimes used for the prediction of pathogens and pest occurrence. Soil temperature in crop simulation models CERES (CERES-Wheat, CERES-maize etc.) is simulated using daily air temperature data, soil moisture status and available water content, albedo, solar radiation and the day of the year. The absence of data of soil temperatures from the canopy is often the limiting factor for crop simulation models. The poorer results of those models were likely caused by inaccurate simulation of ground-level soil temperatures (*Casanova et al., 2006; Wang et al., 2009*). Farmers need this data or a simple algorithm that will enable relatively accurate deduction based on standard measurements of meteorological characteristics. For these purposes, the data regarding soil temperature recorded at standard climatological stations are used. They can differ from actual soil temperatures in or under the crop stands. For these reasons, the collected data should be also compared for different crop stands and soil management systems.

The shape, dimensions and the geometrical structure of a specific plant species play important roles in the development of the canopy microclimate (*Matejka and Huzulák, 1987; Chelle et al., 2009*). *Porté et al. (2004)* pointed out the buffer effect of the forest cover: the daily range was large in the open site (up to 9.7 °C); but it was attenuated in the "pine", the "semi-mature" and the "mixed" stands (up to 3.3 °C, 3.1 °C and 2.0 °C, respectively). *Pierson and Wight (1991)* reported that the amplitude of diurnal variability in

soil temperature (fine loamy over sandy or sandy skeletal soil) in the depth of l cm under sagebrush (*Artemisia tridentata ssp. tridentata*) was similar to the amplitude of the diurnal variability in the depth of 10 cm within the interspaces. The impact of various forest surfaces on the date of reaching the maximum daily soil temperature was studied by *Devine and Harrington (2007)*.

Surface residue cover can affect soil temperature by insulating the soil surface and slowing soil drying in spring (*Fortin, 1993*). Different tillage systems can also influence the temperature of soil and the growth of wheat (*He et al., 2012*). Soil temperature increased in the top 5 cm under strip-tillage (1.2–1.4 °C) over no-tillage and it remained close to the chisel plow soil temperature (*Licht and Al-Kaisi, 2005*). In weed-control experiments by *Han et al. (2013)*, spike numbers were significantly lower under no-tillage than under conventional tillage, possibly because soil temperature under no-tillage was decreased, and hence affected the growth and development of tillers after spring.

The relationship between air and soil temperatures within the agrosystem was described by several studies (for chili, onion and pecan – *Sharma et al., 2010*; for maize and alfalfa – *Luo et al., 1992*; for maize – *Gupta et al., 1981* and others). The specifics of soil temperatures, their vertical stratification under the canopy and the possibilities of data rows reconstruction adapted to the conditions of Czech Republic were described by *Pokladníková and Rožnovský (2006 and 2007)*. The aim of the study by *Krčmářová et al. (2013)* was to evaluate the course of soil temperatures under the wheat canopy, and to determine relationships between soil temperatures under various plant covers.

Nevertheless, there are not many studies evaluating the soil microclimate under the canopy in regard to major field crops suitable for mid-European climate (wheat, barley, potatoes, sugar beet, oil rape). There are significantly more works dealing with soil temperatures for soils under forest stands, including soil temperature modeling based on air temperatures.

The aim of this study was to evaluate the course of soil temperatures under the winter wheat canopy and to determine relationships between soil temperature, air temperature and partly soil moisture.

2. Material and methods

The measurement was performed at the experimental field station Žabčice (Europe, the Czech Republic, South Moravia). The experimental area is located in the floodplain of the Svratka River at an altitude of approximately 184 m a.s.l. in a maize production area. The long-term (1991–2010) average air annual temperature is $10.0\,^{\circ}$C, and the annual precipitation total is 496 mm (*Žalud et al., 2013*). According to the agroclimatic classification (*Kurpelová et al. 1975*), the location belongs to the warm macro area, predominantly warm (annual air sum of effective temperature above $10\,^{\circ}$C 2840 degree days) and dry sub-region (annual potential evapotranspiration minus annual precipitation total 15.5 mm) with mild winters (average of annual absolute minimum air temperatures $-17.4\,^{\circ}$C, annual average number of days with snow cover occurrence 45.6).

Soil types were classified according to *Němeček et al. (2001)*. The soil in the experimental plot Obora (Obo) is heavy clayey-loam Gleyic Fluvisol with 49–58% of the content particles measuring < 0.01 mm. The soil in the experimental plot Pisky (Pis) is medium heavy loamy Haplic Chernozem with 31–32% of the content particles measuring < 0.01 mm.

The experimental field was planted with winter wheat (Sultan variety) in 2010, 2011, and 2013. The spacing of the canopy was 0.125 m between rows, in a population of 3.5 (Obo) and 4.5 (Pis) million plants per ha. At maturity, the average number of spikes was about 610 (Obo) and about 380 (Pis).

Soil and air temperatures were measured by automatic digital temperature sensors (Dallas semiconductor, DS18B20 type). The near surface air temperature sensor was placed in a radiation shield in 0.05 m level above soil surface in wheat canopy. The soil sensors were placed in the soil under the winter wheat canopy in the depths of 0.05, 0.10, and 0.20 m under soil surface. The data were taken and stored in a data logger at fifteen-minute intervals. The hourly values of air and soil temperatures were obtained as the arithmetic average of the fifteen-minute data. The VIRRIB (Amet, Velké Bílovice) sensors were used for measuring the volumetric soil moisture in the Obora locality. The sensors measure hourly temperatures in the 0.10–0.40 m soil profile.

With regard to the technical and time requirements of the exact estab-

lishment of leaf area index – LAI (the practice requires a simple and fast
method of canopy evaluation), canopy growth and its stages were measured
according to the BBCH scale (*Meier, 1997*). The vegetation period of wheat
was divided into three stages: I. BBCH 23–32 (tillering to beginning of stem
elongation), II. BBCH 33–69 (stem elongation to the end of flowering) and
III. BBCH 70–89 (development of fruit and ripening).

The range of the soil temperatures was plotted as a box plot. The regres-
sion analysis was carried out to evaluate interrelationships between soil tem-
peratures measured under the winter wheat canopy and air temperature in
the same canopy. As the course of temperatures in soil can be delayed, cross
correlations were computed for this evaluation (software STATISTICA, ver.
7). These models were tested with the coefficient of determination (R^2).

For soil temperature modeling based on the near surface air temperature
and soil moisture in the 0.10–0.40 profile, the multiple regression method
with quadratic spacing was used (software STATISTICA, ver. 7).

The average soil temperature (from fifteen-minute data) in the Obo lo-
cality, per each year and period, was delineated in the form of 2D nomogram
(software SURFER, ver. 10) by means of the Kriging interpolation method.

3. Results and discussion

Descriptive statistics of the three-year monitoring results (2010, 2011, and
2013) covering soil temperatures under the wheat canopy in three depths
(0.05, 0.10 and 0.02 m) on two localities (Obo and Pis) with different soil
conditions are displayed in Fig. 1. The 2012 experiment was damaged by
drought. The average soil temperatures in the course of the main vege-
tation period of winter wheat ranged from 12.46 °C (Obo, 0.20 m, 2011)
to 16.43 °C (Pis, 0.05 m, 2011). The maximum difference between locali-
ties with respect to the average vegetation soil temperatures was found in
2011, at 20 cm (Obo 12.46 °C, Pis 15.96 °C). A distinctive difference be-
tween localities caused by diverse soil conditions and canopy structure was
confirmed. Meteorological conditions were identical on both localities as the
distance between the trial plots was minimal (ca 2 km). Especially in 2010
which was a year with a lot of precipitation, minimal differences among soil
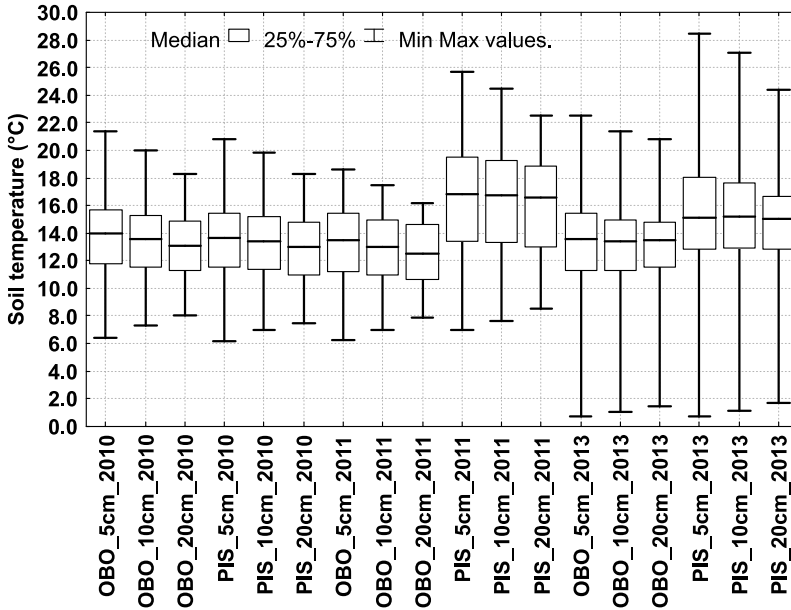temperatures in different depths and also between localities were found (the

Fig. 1. The range of soil temperatures under winter wheat canopy and its descriptive statistics. Notes: OBO_5cm_2010 = Obora locality, 0.05 m depth, 2010 year, etc.

difference among the average values was only 0.83 °C). This is also evident from Fig. 2 which displays the sums of effective soil temperatures above 5 °C in the depth of 0.05 m and describes the dynamics of soil temperatures in the course of time. The presented phenomenon which is related to energy balance and heat flux into the soil for different plant canopies (*Hurtalová and Matejka, 1999*) was caused by abnormal precipitation, below-average sunshine (sunshine hours) values and high production of biomass. Vegetation cover increased (corrected) the soil surface temperatures at night by reducing convective and radiative heat loss from the ground surface.

This is also manifested in the year-on-year soil temperatures evaluation from the Obo locality (average in the profile of 0.05–0.20 m in 2010 – 13.45 °C and standard deviation 2.84, in 2011 12.83 °C and 2.52, in 2013 12.69 °C and 4.19). The low difference of mean soil temperature values and their dynamics in the course of the vegetation season are influenced by higher water content in heavy soil and a high level of underground wa-
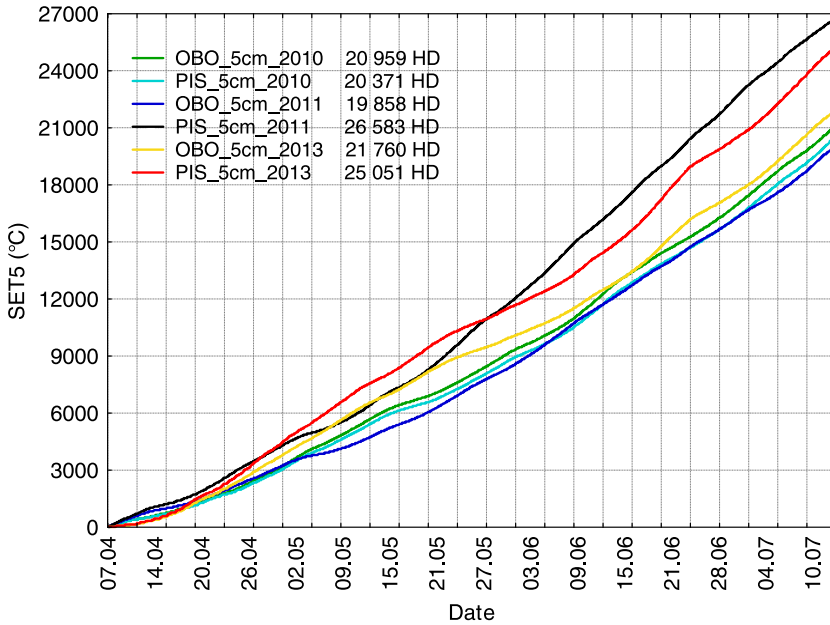
214

Fig. 2.   Dynamics of soil temperatures under winter wheat canopy during vegetation periods expressed as the sum of hourly effective temperatures above 5 °C. Notes: OBO_5cm_2010 = Obora locality, 0.05 m depth, 2010 year, etc.; HD = hourly degrees.

ter. In contrast, the Pis locality (medium to light soil on the gravel) shows higher soil temperatures and amplitudes. The average soil temperature in the 0.05–0.20 m profile was 13.23 °C in 2010 and the standard deviation was 2.85, in 2011 the average soil temperature was 16.22 °C and 3.78, in 2013 15.14 °C and 4.07.

The course of soil temperatures during vegetation, expressed in Fig. 2 as a cumulative sum of temperatures above 5 °C (SET5), is also important for prediction and signalization of poikilotherm organisms (pests). In connection with soil pest Western Corn Rootworm occurrence prediction, the hourly and daily soil sum of effective temperatures in the maize canopy in Czech Republic was evaluated by *Středa et al. (2013)*. Likewise, similar study was carried out in Switzerland by *Derron et al. (2005)*. For most pests, the temperature of soil in the upper part of the soil profile is of key importance. Average daily increase of SET5 at 0.05 m (three-year monitor-

ing) was 215 hourly degree (HD) on the Obo locality, 247 HD on the Pis locality (that is 15% difference). The maximum difference of seasonal SET5 values on the Obo and Pis localities (Fig. 2) is 6725 HD. It is interesting that the highest as well as lowest SET5 values were reached in 2011. This is mainly a result of different temperature and moisture regimes of light and heavy soils, meteorological conditions during the vegetation season and the distinctive impact of the canopy (varied canopy structures were used). It is well known that the soil surface temperature is highly correlated with light penetration through the canopy. In the study of *Prévost and Pothier (2003)*, significant increases by several degrees of summer soil temperature were found in the 50, 65 and 100% cuttings of a mixed aspen-conifer stand.

Sándor and Fodor (2012) present that the crop cover significantly influences the soil temperature dynamics of the upper soil layers. Therefore, considering the LAI in a model calculation is indispensable. In this respect, the vegetation period of winter wheat was divided into three stages in our experiment. Detailed course of daily soil temperatures and their stratification within the soil profile were expressed by means of 2D nomograms (Fig. 3–5) for each vegetation period. Data from the Obo locality during vegetation periods I to III in 2010, 2011 and 2013 were used for creation of the nomograms. Based on this data, it is possible to describe the daily regime of soil temperatures under the winter wheat canopy during important growth stages. The impact of winter wheat, spring barley and ley in comparison with bare soil (heavy clay) during the growth period was also studied by *Rodskjer et al. (1989)*. In the case of spring barley, the effect of the stand on soil temperature ocurred in the upper soil layer when leaf area index was about 1. The lag of an obvious temperature difference between the bare soil and the barley increased with depth.

Furthermore, the detailed time and vertical profiles of soil temperatures enable estimation of their impact on pedo-chemical, pedo-biological and phenological processes. However, for example, *McMaster and Wilhelm (1998)* presented that in no instance did soil temperature significantly improve prediction of winter wheat phenology (in comparison with air monitoring outcomes). Exact quantification of year-on-year soil temperature difference, even in depths where direct monitoring is not carried out, can be conducted by means of interpolated values. In the case of annual soil temperature monitoring, zero degree isotherm is identified (*Středová et al.,*
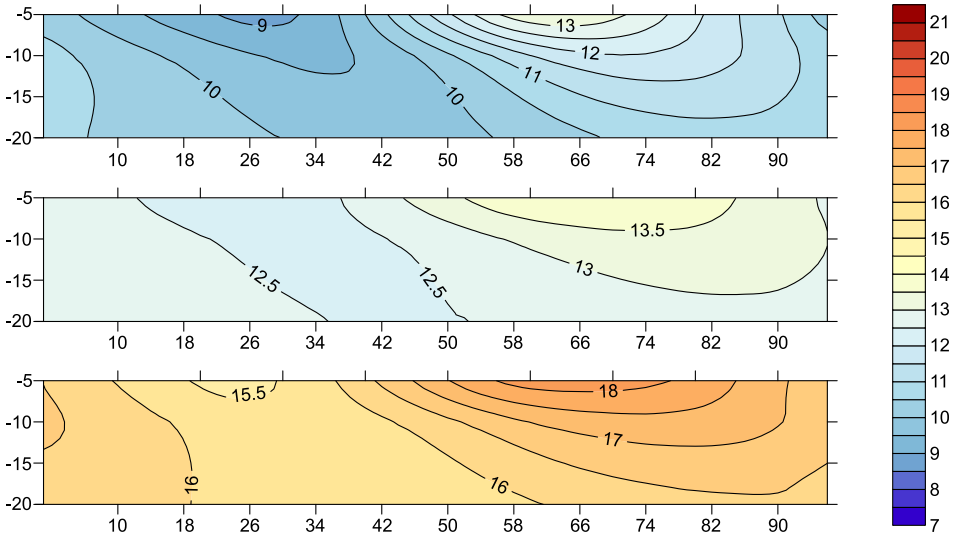
Fig. 3. 24-hour course (x-axis, expressed in 15-minute intervals) of soil temperatures (°C) in the 0.05–0.20 m soil profile (y-axis, expressed in centimetre) in 2010 (Obo locality), from above: 1st, 2nd and 3rd stages.
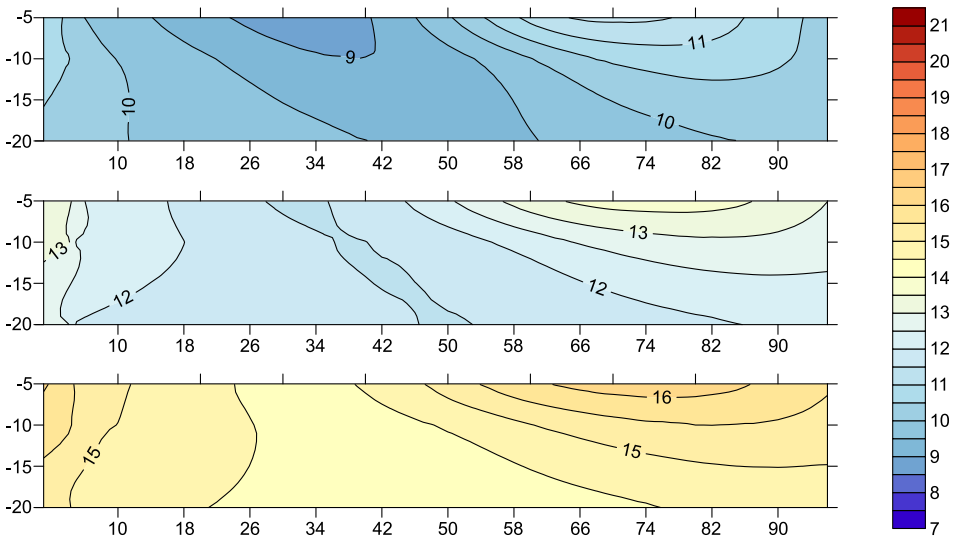

Fig. 4. 24-hour course (x-axis, expressed in 15-minute intervals) of soil temperatures (°C) in the 0.05–0.20 m soil profile (y-axis, expressed in centimetre) in 2011 (Obo locality), from above: 1st, 2nd and 3rd stages.
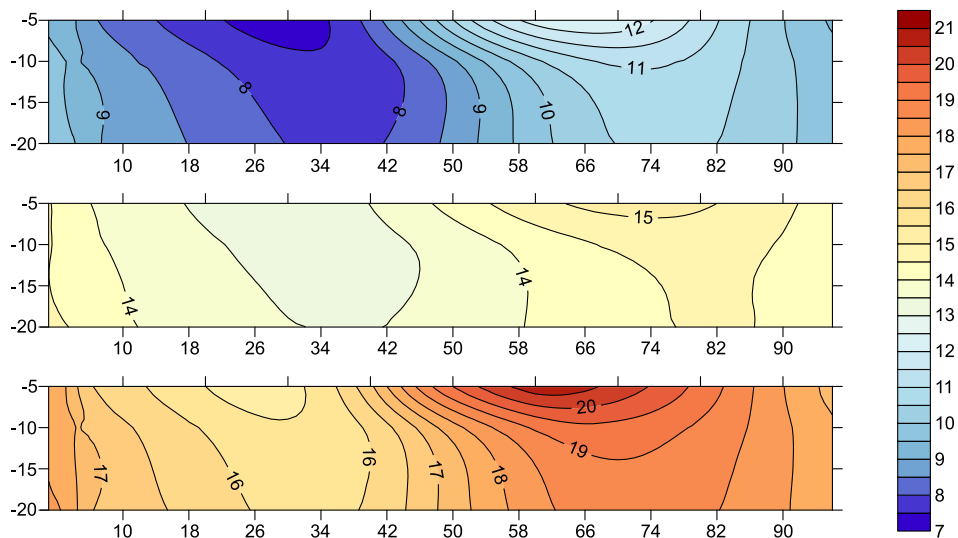
217

Fig. 5. 24-hour course (x-axis, expressed in 15-minute intervals) of soil temperatures (°C) in the 0.05–0.20 m soil profile (y-axis, expressed in centimetre) in 2013 (Obo locality), from above: 1st, 2nd and 3rd stages.

2012).

The dependence of hourly soil temperature under winter wheat canopy on the hourly near surface air temperature was also evaluated (Table 1). However, the prediction of soil temperature in the winter wheat canopy can not be done from the air temperature in the ground of winter wheat canopy recorded at the same time (for example *Krčmářová et al., 2013*). As it was found out by a cross correlation analysis, the best interrelationships between these two variables were achieved after a 3-hour delay for the soil temperature in 0.05 m, 5-hour delay for 0.10 m and 8-hour delay for 0.20 m. After the time correction, the determination coefficient reached values from 0.75 to 0.89 for the depth of 0.05 m, 0.61 to 0.82 for the depth of 0.10 m and 0.33 to 0.70 for the depth of 0.20 m. *Sándor and Fodor (2012)* who carried out their studies under climatical conditions similar to those in Czech Republic reported that the peak soil temperature (calcaric arenosol) in the depth of 0.05 m occurred 6 hours later than the peak of the air temperature. Their results differ from ours mainly due to the distinctly different canopy character (wide row spaced maize vs. narrow row spaced wheat).

Table 1. Regression analysis of dependence of hourly soil temperatures on hourly air temperatures in winter wheat canopy

Year	Stage	-0.05 m	-0.10 m	-0.20 m
2010	I	y = 0.5348x + 5.5539 $R^2 = 0.8329$	Y = 0.3772x + 6.9439 $R^2 = 0.6691$	y = 0.2348x + 8.1385 $R^2 = 0.4112$
	II	y = 0.5971x + 5.2177 $R^2 = 0.8427$	y = 0.452x + 6.923 $R^2 = 0.7199$	y = 0.2967x + 8.7678 $R^2 = 0.5199$
	III	y = 0.5649x + 7.0587 $R^2 = 0.8794$	y = 0.4104x + 9.3943 $R^2 = 0.7422$	y = 0.2516x + 11.704 $R^2 = 0.4866$
2011	I	y = 0.3526x + 6.8404 $R^2 = 0.7619$	y = 0.2512x + 7.6228 $R^2 = 0.6145$	y = 0.1319x + 8.6932 $R^2 = 0.3344$
	II	y = 0.4522x + 6.872 $R^2 = 0.8131$	y = 0.3426x + 7.9506 $R^2 = 0.6605$	y = 0.2144x + 9.2579 $R^2 = 0.3998$
	III	y = 0.3678x + 9.7235 $R^2 = 0.8091$	y = 0.2538x + 11.21 $R^2 = 0.6837$	y = 0.1208x + 12.924 $R^2 = 0.4004$
2013	I	y = 0.6946x + 2.7475 $R^2 = 0.8855$	y = 0.6155x + 3.1928 $R^2 = 0.8199$	y = 0.5409x + 3.9885 $R^2 = 0.7007$
	II	y = 0.4282x + 7.5356 $R^2 = 0.7527$	y = 0.3753x + 8.1763 $R^2 = 0.6862$	y = 0.3349x + 8.8461 $R^2 = 0.6219$
	III	y = 0.4639x + 9.537 $R^2 = 0.8067$	y = 0.3496x + 11.306 $R^2 = 0.6816$	y = 0.2388x + 13.332 $R^2 = 0.4043$

The coefficient of determination (Table 1) reaches values from 0.33 to 0.89 in dependence on the growth stage of plants and the depth of measurement. This coefficient differs slightly in the 0.2 m depth. From this point of view, it is possible to predict soil temperatures under winter wheat canopy from data of air temperature recorded in the near surface area in dependence on the winter wheat developmental stage. A similar analysis – prediction of daily soil temperature under the wheat canopy by air temperature was carried out by *Ahmad and Rasul (2008)*. The coefficient of determination (R^2) ranged between 0.319 in the depth of 20 cm in the winter period (main vegetation period of wheat) and 0.865 in the depth of 0.10 m in spring. *Toy et al. (1978)* showed that air temperature may be viewed as a surrogate for soil temperature – a linear relationship between monthly soil and air temperatures has been found. *Zheng et al. (1993)* achieved good results in respect to modeling soil temperatures under the forest canopy by employing air temperatures and the leaf area index data according to the

Beer-Lambert Law.

Modeling of hourly soil temperature under the winter wheat canopy for the depth of 0.05 m in April until July 2011 (Obo locality) was also performed. Correlation among variables was defined by linear regression of the hourly near surface air temperature (i.e. in 0.05 m height above soil surface) in the canopy and the delayed hourly soil temperature under canopy (outcome of cross correlation). The difference among the measured and modeled soil temperatures was -5.06 to $2.72\,°$C. When using multiple regression with quadratic spacing (modeling of hourly soil temperature in under canopy based on the hourly near surface air temperature and hourly soil moisture in the 0.10–0.40 m profile), the difference between the measured and modeled soil temperatures in the depth of 0.05 m was -2.16 to $2.37\,°$C. The regression equation $-21.5049+2.2846\times x+2.5909\times y-0.0127\times x^2-0.0822\times x\times y-0.0618\times y^2$ (when x = hourly near surface air temperature in 0.05 m height in $°$C and y = hourly soil moisture in 0.10–0.40 m profile in volume %) enables relatively accurate modeling of soil temperatures ($R^2 = 0.93$) when compared with using alternative agrometeorological instruments.

4. Conclusion

The impact of year, locality (soil), winter wheat canopy structure and the growth stage on the soil temperature in various depths was determined. Detailed course of daily soil temperatures and their stratification in the soil profile for individual vegetation periods was expressed by 2D nomograms. The time delay of the air temperature course in the canopy and soil temperatures under canopy was quantified by cross correlation. The regression between soil temperature, air temperature and partly soil moisture in the winter wheat stand was established. These findings can be used in making more accurate prediction models of pathogens and pest occurrence on winter wheat, in models of crop and yield development, soil evaporation, soil heat fluxes etc.

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