Maize transpiration in response to meteorological conditions

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Abstract: Differences in transpiration of maize (*Zea mays* L.) plants in four soil moisture regimes were quantified in a pot experiment. The transpiration was measured by the "Stem Heat Balance" method. The dependence of transpiration on air temperature, air humidity, global solar radiation, soil moisture, wind speed and leaf surface temperature were quantified. Significant relationships among transpiration, global radiation and air temperature (in the first vegetation period in the drought non-stressed variant, r = 0.881**, r = 0.934**) were found. Conclusive dependence of transpiration on leaf temperature (r = 0.820**) and wind speed (r = 0.710**) was found. Transpiration was significantly influenced by soil moisture (r = 0.395**, r = 0.528**) under moderate and severe drought stress. The dependence of transpiration on meteorological factors decreased with increasing deficiency of water. Correlation between transpiration and plant dry matter weight (r = 0.997**), plant height (r = 0.973**) and weight of corn cob (r = 0.987**) was found. The results of instrumental measuring of field crops transpiration under diverse moisture conditions at a concurrent monitoring of the meteorological elements spectra are rather unique. These results will be utilized in the effort to make calculations of the evapotranspiration in computing models more accurate.

Key words: transpiration, sap flow, stem heat balance, soil moisture, meteorological elements

1. Introduction

Availability of soil water together with global radiation and the saturation deficit belong to the main agrometeorological elements which determine the transpiration performance of plants (*Du et al., 2011; She et al., 2013; Zep-*

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pel et al., 2008). The course of the meteorological elements impacts the transpiration flow of plants (*Naithani et al., 2012*) and the total evapotranspiration. Global radiation has a primary effect on transpiration of plants (*Gao et al., 2010*), however, in case of drought stress occurrence, one may expect a major influence of soil moisture on the course of transpiration (*Novák et al., 2005*). A crop's reaction to the decrease soil water capacity is different for dissimilar crop species. High evapotranspiration requirements of the environment may cause loss of soil water supplies through excessive transpiration in non-sensitive plants (*Yang et al., 2012*).

Water shortage-induced stress often goes hand in hand with temperature stress. Transpiration is the main mechanism of plant protection against over-heating. Leaf temperature rises with the increase of the air temperature (*Živčák, 2010*). Wheat leaf temperature impacted the speed of transpiration (*Farooq et al., 2011*).

Various methods are used for quantification of plants transpiration in correlation to environmental conditions. Besides modeling based on meteorological elements, instrumental methods are utilized as well. They are based on measuring temperature changes caused by the sap flow effect. Methods for the detection of sap flow which are currently available apply heat transmission by water contained in the xylem. These methods include the "heat pulse method" which monitors gradual flow velocity based on a heat pulse motion in a shortly heated part of the trunk/stem. This method was published by Huber in as early as 1932 (*Šantrůček, 1998*). The "thermal dissipation method" is related to the correlation between the temperature of a heated sensor and flow density (*Granier, 1985*). The "stem heat balance method" (SHB) (*Kučera et al., 1977; Ishida et al., 1991; Lindroth et al., 1995*) and the "trunk sector heat balance method" (*Smith and Allen, 1996*) employ direct electrical heating of tissue and inner heat monitoring. The outcomes completed with meteorological and physiological characteristics can be used to assess individual subjects as well as forest stands and field crops canopies.

The aim of this work was (i) to identify differences in transpiration of maize plants exposed to various conditions of water supply, and (ii) to characterize the dependence of transpiration on meteorological and agrometeorological elements (air temperature, global solar radiation, soil moisture etc.) and plant traits.

2. Material and methods

A pot trial was established under natural conditions with limited rainfall. Based on physical soil analysis (full water holding capacity: 39 volume percent; permanent wilting point: 21 volume percent), four variants of irrigation were tested. Sap flow measurement was started at the stem elongation in phenological growth stage BBCH 39 (the BBCH – scale is a system for a uniform coding of phenologically similar growth stages of plant species; *Meier, 1997*): (A) control: 75% available water holding capacity (AWHC); (B) mild stress: 50% AWHC; (C) medium stress: 25%; and (D): significant stress: 15% AWHC (23% soil moisture). In each pot (200 dm^3), 6 maize plants were sown (breeding line 2087, provided by CEZEA Čejč). Phenological data were monitored continuously and in the later phase of the trial, changes of conformation as a result of stress were studied, too. Transpiration was monitored by means of a continuous measuring of sap flow in 10-minute interval. The EMS 62 system (EMS, Brno) uses the SHB method (*Kučera et al., 1977*) was used. Sap flow (Q, $kg.h^{-1}$) was measured on two plants per pot from heading (BBCH 50) to full maturity (BBCH 89). Moreover, the following meteorological variables were monitored:

(i) relative air humidity (%) and air temperature (°C) by HOBO RH Temp sensors (Onset Computer Co.) in 10-minute intervals,

(ii) volumetric soil moisture (%) by automatic electromagnetic sensors VIRRIB (AMET, Velké Bílovice) in 15-minute intervals,

(iii) global solar radiation ($W.m^{-2}$) measured by LI-COR sensors (LI-COR) in 15-minute intervals,

(iv) leaf surface temperature (°C) by infrared thermometer Raytek MX4 Raynger® MX4™ in 1-minute intervals; the sensor measures the surface temperature with resolution of 0.1°C and accuracy of 1.0°C,

(v) wind speed in canopy ($m.s^{-1}$) by anemometer W1 (Tlusťák, Praha) in 10-minute intervals.

Data were processed by MINI32 software (EMS, Brno) and statistically analyzed, i.e. correlation analysis, analysis of variance including mean comparison by Tukey's LSD test, using STATISTICA 10 (StatSoft Inc., Tulsa, OK) were performed.

Data of sap flow, i.e. transpiration intensity and meteorological data, were always evaluated only for the light part of a day (from sunrise to sunset).

3. Results and discussion

The measuring period was divided into three periods according to changes in transpiration and plant phenology (1: 27th July to 6th August 2012; 2: 7th to 24th August 2012; 3: 25th August to 14th September 2012). Dependency of transpiration on meteorological factors (global radiation, air temperature) was assessed for each period separately so that variability of monitored features was closely recorded.

Table 1 shows the strongest relationships among transpiration and air temperature and/or radiation for all irrigation treatments in period 1. During the growing season, this dependency decreases most in the stressed variants. In period 3, an increase of dependency on radiation and temperature is evident in the variants with more water supplies. A significant positive correlation between radiation and sap flow was also observed in cassava (*Oguntunde, 2005*), maize (*Li et al., 2011*), and soybean (*Gerdes et al., 1994*).

Dependency of sap flow on meteorological parameters decreases with increasing water stress. The non-significant correlation for variant D are

Table 1. Correlation of sap flow to temperature and global radiation with respect to the different irrigation treatments (** P ≤ 0.01; * P ≤ 0.05)

Variant	Variable	Period 1	Period 2	Period 3
A	Air Temperature	0.934**	0.627**	0.665**
	Global Radiation	0.881**	0.670**	0.640**
B	Air Temperature	0.862**	0.537*	0.674**
	Global Radiation	0.873**	0.500*	0.722**
C	Air Temperature	0.902**	0.516*	0.681**
	Global Radiation	0.699*	0.604**	0.773**
D	Air Temperature	0.698*	0.030	0.022
	Global Radiation	0.439	0.563*	0.101

caused by long-term drought stress duration. Drought stress during the period 3 gave rise to early senescence of maize plants with impact on transpiration.

Correlation coefficients were determined for average diurnal values of sap flow and soil moisture from the total growing season. A statistically highly significant dependence was discovered in variants C (r = 0. 395**) and D (r = 0.528**). The effect of air temperature and humidity on transpiration was also demonstrated for sagebrush (*Artemisia tridentata* var. *vaseyana*) in US semi-desert conditions (*Naithani et al., 2012*). However, these plants only showed weak dependence of transpiration on radiation values. This discrepancy with our results may be explained by different conditions in semi-desert environments where plants are not limited by the lack of solar radiation. A greater share of radiation, temperature and air humidity on transpiration values in maize was shown by *Irmak and Mutiibwa (2010)*. Only a lesser part of variability was explained by soil moisture. A close correlation of radiation and vapour pressure deficit versus soil moisture and type of plant was proved by sap flow measurement in *Quercus liaotungensis* and *Robinia pseudoacacia* (*Du et al., 2011*). A significant dependence of sap flow on soil moisture in *Caragana korshinskii* was observed by *She et al. (2013)*.

In period 1, similar sap flow was observed for variants A and B plants which decreased with time as suboptimal conditions continued. In period 3, plants in variant D terminated growth due to persistent water deficit stress (Table 2). *Du et al. (2011)* also indicated an effect of plant type and phenology on sap flow capacity. *Pivec et al. (2009)* confirmed an effect of maturity and senescence on sap flow of winter rapeseed.

Plant sap flow capacity reached as much as 45 g of water per hour during the day. Similar maize sap flow values were observed in a pot trial by

Table 2. Average diurnal values of sap flow ($kg.h^{-1}$) per plant

	Period 1	Period 2	Period 3
variant A	0.01861a	0.01044a	0.00319a
variant B	0.01290ab	0.00668b	0.00287a
variant C	0.00701b	0.00510b	0.00341a
variant D	0.00698b	0.00404b	0.00003b

Note: Statistically different values are indicated by different letters.

Gavloski et al. (1992) and in a field trial by *Bethenod et al. (2000). Kjelgaard et al. (1997)* determined the average maize transpiration value to be between 41 and 44 g.h^{-1}. Significant differences among irrigation treatments were observed for diurnal sap flow (Table 2). In period 1, i.e. flowering stage, significant differences were identified among variants A, B and D. In period 2, plant transpiration in the control variant was significantly different from the stressed variants. In period 3, a significant differences were observed among variant D and the other irrigation treatments. Even though transpiration is much dependent on the weather, different irrigation schedules caused significant differences of transpiration in individual variants. Significant differences of sap flow in grapevine of irrigated and water-stressed variants were identified by *Escalona et al. (2002). Gavloski et al. (1991)* observed increasing differences of sap flow between control and drought treatments of increasing water stress.

Wu et al. (2011b) recorded a statistically significant drop in transpiration of maize plants when AWHC of soil decreased by 20% under the level of full water capacity. On the contrary, the calculated evapotranspiration in maize canopy was influenced when AWHC dropped to a value as low as 58.2% (*Matejka et al., 2005*). In the barley trial by *Jamieson et al. (1995)*, change of plants transpiration occurred at AWHC values under 65%.

Maize sensitivity to stress by drought changes during a vegetation period. *Zinselmeier et al. (2002)* and *Doorenbos and Kassam (1979)* found that maize's highest sensitivity to stress occurs in the course of flowering. In our trial, maize was tested in the heading phase as well as the flowering phase. Drought affected generative plant organs in a considerable way. The effect of drought on grain production has been confirmed by *Cakir (2004)* who also observed significant decrease in grain yield in maize plants which were not irrigated during heading and flowering.

In period 3, dry matter accumulation was mostly impacted by transpiration. Correlation between sap flow and total plant dry matter weight was r = 0.997**. Sap flow capacity also affected the weight of cobs (r = 0.987**). Most plants in variant D produced small or no cobs; a statistically significant difference was found between variant D and the other irrigation treatments.

Although plants in the control variant A (75% AWHC) were not subjected to moisture stress, they produced dry matter yield by less then 2%

higher compared to variant B (50% AWHC). In comparison to variant C (25% AWHC), the yield was even by 3% lower. Plants in variant D (15% AWHC) produced yield lower by 20%. Water stress did not affect biomass production as much as was presumed according to the decrease of sap flow.

Sap flow in the mildly stressed variant B dropped by 30% in comparison to the control, and variant D transpired by almost 70% less. Likewise, *Wu et al. (2011a)* observed a smaller impact of soil moisture on dry matter creation than on transpiration intensity in maize plants.

The gained results enable us to identify meteorological parameters which affect transpiration directly and thus simulate the transpiration procedure in a given variety of maize. A function expressing the relations among global radiation, air temperature and sap flow was calculated for individual phenological stages. The function was derived for sap flow under non-stressed conditions.

Sap flow as per average diurnal radiation level (y) and average diurnal air temperature (x) for period 1 is described by the equation ($\mathrm{r}^2 = 0.977$):

$$z = (a + bx + cy)/(1 + dx + fy),$$

where: $a = -1.07.10^{-3}$; $b = 8.24.10^{-6}$; $c = 1.92.10^{-5}$; $d = -2.79.10^{-2}$; $f = 5.14.10^{-5}$

Sap flow as per average diurnal radiation level (y) and average diurnal air temperature (x) for period 2 is described by the equation ($\mathrm{r}^2 = 0.919$):

$$z = (a + b.ln(x) + c.ln(y))/(1 + dx + fy),$$

where: $a = -4.03.10^{-3}$; $b = -9.21.10^{-4}$; $c = 1.65.10^{-3}$; $d = -2.40.10^{-2}$; $f = -6.06.10^{-4}$.

Sap flow as per average diurnal radiation level (y) and average diurnal air temperature (x) for period 3 is described by the equation ($r^2 = 0.823$):

$$z = a^{(b/x+c.y)}$$

where: $a = 8.29.10^{-1}$; $b = -1.82.10^{2}$; $c = 1.08.10^{-2}$.

In the case of stress by drought, the transpiration in maize is less dependent on the course of diurnal values of global radiation and air temperature. Increase of transpiration starts to occur at higher air temperatures in comparison with the non-stressed variant. Radiation values mainly in period 1 do not statistically significantly impact transpiration intensity. For the above mentioned periods, a function describing correlation of the measured meteorological elements and transpiration of plants in pot D (stress by drought on the level of 15% AWHC) was calculated. For period 3, no function describing the correlation with adequate accuracy was found.

The transpiration of a maize plants by high transpiration demands of the atmosphere

Increased demand for water expenditure by transpiration occurs mainly during days with high air temperatures and radiation. This phenomenon is proved by the course of transpiration in 24th – 26th July, 2013, when the studied meteorological elements were continually recorded in detailed one-minute steps, including wind speed and leaf surface temperatures. The amount of soil water available for plants reached 38% (95% of AWHC), which is almost full soil water capacity. Transpiration was statistically significantly influenced by all measured elements. Statistically significant effect of studied meteorological elements on maize transpiration has also been confirmed by *Gao et al. (2010)*. Global radiation had major influence on the rate of transpiration. Water expenditure by plants reached 0.033 $kg.h^{-1}$ on average, the maximum was 0.058 $kg.h^{-1}$. The correlations among measured elements, leaf area temperature and transpiration are described in Table 3.

Table 3. Correlation coefficients of dependence among transpiration and selected meteorological elements and leaf area temperature

	Global radiation	Wind speed	Air temperature	Air humidity	Leaf temperature
Correlation coefficient	0.650**	0.710**	0.810**	-0.660**	0.820**

Cross correlation of data was calculated and time distance of the transpiration reaction to abiotic factors was established. The fastest reaction was observed when air humidity and temperature (Fig. 1) and wind speed (0–3 minutes) changed. Increase of the leaf temperature caused increased rate of transpiration in a time period of 5 minutes (Fig. 2). 10 minutes after changing the radiation intensity, the plant reacted by altering its transpiration.

A distinct effect of leaf and air temperature on transpiration became evident. A strong correlation between leaf temperature and transpiration (r = 0.820**) confirms the possibility of concurrent effect of stress by drought

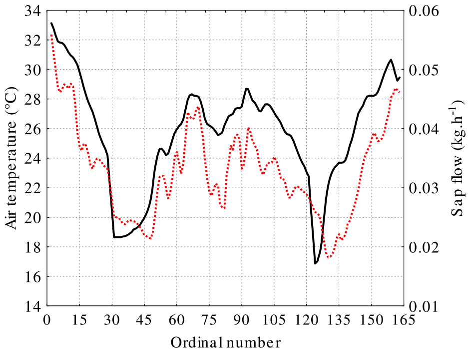

Fig. 1. Course of sap flow (dotted red line; kg.h^{-1}) in dependence on air temperature changes (solid black line; °C).

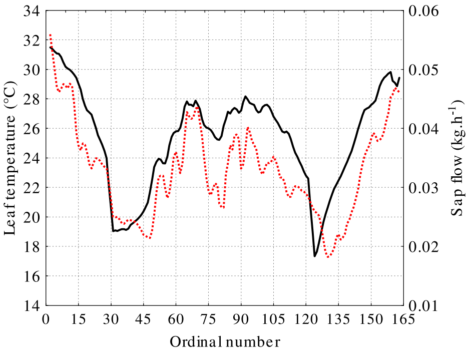

Fig. 2. Course of sap flow (dotted red line; kg.h^{-1}) in dependence on leaf area temperature changes (solid black line; °C).

and high temperatures on the physiological state of a plant. Positive correlation between transpiration and leaf temperature in maize and wheat was reported by *Zhao et al. (2011)*. Reaction of leaf temperature to air temperature changes was instant with no time delay.

Wind speed (Fig. 4) influenced sap flow more distinctly than global radiation did (Fig. 3). Radiation values in the course of measuring in 2013 ranged between 200–500 W.m^{-2}. Radiation intensity did not manifest it-

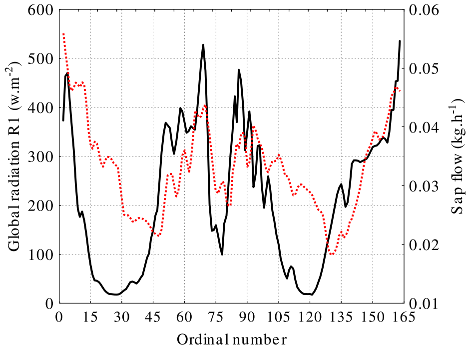

Fig. 3. Course of sap flow (dotted red line; kg.h^{-1}) in dependence on global radiation intensity (solid black line; W.m^{-2}).

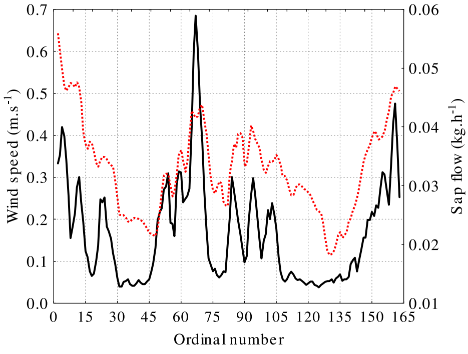

Fig. 4. Course of sap flow (dotted red line; kg.h^{-1}) in dependence on wind speed (solid black line; m.s^{-1}).

self as one of major determinants of sap flow (r = 0.650**). The average wind speed in canopy reached 0.2 $m.s^{-1}$. But even a low speed of wind flow increased sap flow intensity.

4. Conclusion

Measuring of transpiration flow (sap flow) is a way to quantify utilization/flow of water by plants in dependence on environmental factors. The "Stem heat balance" (SHB) method was selected as an accurate, sensitive method for sap flow detection in maize. The aim was to establish the degree of the effect of selected agrometeorological elements on sap flow. At the same time, stress induced by drought and its influence on the course of sap flow were studied.

Highly significant correlation coefficient values were found for sap flow and global radiation performance and for sap flow and air temperature. Simultaneously, statistically significant differences among sap flow values and selected irrigation regimes were quantified. Although sap flow is strongly affected by the global radiation performance and saturation supplement, the effect of water deficiency became evident. In comparison to field conditions, soil moisture in a pot trial had a greater impact on sap flow (water availability is limited by pot size). Nevertheless, the information capacity of this experiment is significant in this case.

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References

Bethenod O., Katerji N., Goujet R., Bertolini J. M., Rana G., 2000: Determination and validation of corn crop transpiration by sap flow measurement under field conditions. Theoretical and Applied Climatology, **67**, 153–160.

Cakir R., 2004: Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Research, **89**, 1–16.

Doorenbos J., Kassam A. K., 1979: Yield response to water. Irrigation and Drainage Paper. FAO, United Nations, Rome, **33**, 176 p.

Du S., Wang Y-L., Kume T., Zhang J-G., Otsuki K., Yamanaka N., Liu G-B., 2011: Sapflow characteristics and climatic responses in three forest species in the semiarid Loess Plateau region of China. Agricultural and Forest Meteorology, **151**, 1–10.

Escalona J., Flexas J., Medrano H., 2002: Drought effects on water flow, photosynthesis and growth of potted grapevines. Vitis, **41**, 57–62.

Farooq M., Bramley H., Palta J. A., Siddique K. H. M., 2011: Heat stress in wheat during reproductive and grain-filling phases. Critical Reviews in Plant Sciences, **30**, 491–507.

Gao Y., Duan A. W., Qiu X. Q., Zhang J. P., Sun J. S., Wang H. Z., 2010: Plant transpiration in a maize/soybean intercropping system measured with heat balance method. Chinese Journal of Applied Ecology, **21**, 1283–1288.

Gavloski J. E., Ellis C. R., Whitfield G. H, 1992: Effect of restricted watering on sap flow and growth in corn (*Zea mays* L.). Canadian Journal of Plant Science, **72**, 361–368.

Gerdes G., Allison B. E., Pereira L. S., 1994: Overestimation of soybean crop transpiration by sap flow measurements under field conditions in Central Portugal. Irrigation Science, **14**, 135–139.

Granier A., 1985: Une nouvelle méthode pour la mesure dy flux de sève brute dans le trons des arbres. Annales Scientifique Forestiere, **22**, 193–200 (in French).

Irmak S., Mutiibwa D., 2010: On the dynamics of canopy resistance: Generalized linear estimation and relationships with primary micrometeorological variables. Water Resources Research, **46**, doi:10.1029/2009WR008484.

Ishida T., Campbell G. S., Calissendorff C., 1991: Improved heat balance method for determining sap flow rate. Agricultural and Forest Meteorology, **56**, 35–48.

Jamieson P. D., Francis G. S., Wilson D. R., Martin R. J., 1995: Effects of water deficits on evapotranspiration from barley. Agricultural and Forest Meteorology, **76**, 41–58.

Kjelgaard J. F., Stockle C. O., Black R. A., Campbell G. S., 1997: Measuring sap flow with the heat balance approach using constant and variable heat inputs. Agricultural and Forest Meteorology, **85**, 239–250.

Kučera J., Čermák J., Penka M., 1977: Improved thermal method of continual recording the transpiration flow rate dynamics. Biologia Plantarum, **19**, 413–420.

Li H., Liu Y., Cai J., Mao X., 2011: Change of sap flow rate and stem diameter microvariation of summer maize and influent factors. Transactions of the Chinese Society of Agricultural Engineering, **27**, 187–191.

Lindroth A., Čermák J., Kučera J., Cienciala E., Eckersten H., 1995: Sap flow by heat balance method applied to small size Salix-trees in a short-rotation forest. Biomass and Bioenergy, **18**, 7–15.

Matejka F., Hurtalová T., Rožnovský J., Chalupníková B., 2005: Effect of soil moisture on evapotranspiration of a maize stand during one growing season. Contrib. Geophys. Geod., **35**, 3, 219–228.

Meier U., 1997: BBCH-Monograph. Growth stages of plants – Entwicklungsstadien von Pflanzen – Estadios de las plantas – Développement des Plantes. Blackwell Wissenschaftsverlag, Berlin und Wien, 622 p.

Naithani K. J., Ewers B. E., Pendall E., 2012: Sap flux-scaled transpiration and stomatal conductance response to soil and atmospheric drought in a semi-arid sagebrush ecosystem. Journal of Hydrology, **464-465**, 176–185.

Novák V., Hurtalová T., Matejka F., 2005: Predicting the effects of soil water content and soil water potential on transpiration of maize. Agricultural Water Management, **76**, 211–223.

Oguntunde P. G., 2005: Whole-plant water use and canopy conductance of cassava under limited available soil water and varying evaporative demand. Plant and Soil, **278**, 371–383.

Pivec J., Brant V., Bečka D., 2009: The influence of weather conditions on the sap flow of *Brassica napus* L. during the fructification and maturation stages. Ekológia, **28**, 43–51.

She D., Xia Y., Shao M., Peng S., Yu S., 2013: Transpiration and canopy conductance of Caragana korshinskii trees in response to soil moisture in sand land of China. Agroforestry Systems, **87**, 667–678.

Smith D. M., Allen S. J., 1996: Measurement of sap flow in plant stems. Journal of Experimental Botany, **47**, 1833–1844.

Šantrůček J., 1998: Vodní režim rostlin. In: Procházka S., et al.: Fyziologie rostlin. Academia, Praha, 52–88 (in Czech).

Wu Y. Z., Huang M. B, Warrington D. N., 2011a: Responses of different physiological indices for maize (*Zea mays*) to soil water availability. Pedosphere, **21**, 639–649.

Wu Y. Z., Huang M. B., Warrington D. N., 2011b: Growth and transpiration of maize and winter wheat in response to water deficits in pots and plots. Environmental and Experimental Botany, **71**, 65–71.

Yang Z., Sinclair T. R., Zhu M., Messina C. D., Cooper M., Hammer G. L., 2012: Temperature effect on transpiration response of maize plants to vapour pressure deficit. Environmental and Experimental Botany, **78**, 157–162.

Zeppel M. J. B., Macinnis-Ng C. M. O., Yunusa I. A. M., Whitley R. J., Eamus D., 2008: Long term trends of stand transpiration in a remnant forest during wet and dry years. Journal of Hydrology, **349**, 200–213.

Zhao F., Wang Q., Wang J., Wang J., Ouyang Z., Yu G., 2011: Photosynthesis-transpiration coupling mechanism of wheat and maize during daily variation. Acta Ecologica Sinica, **31**, 7526–7532.

Zinselmeier C., Sun Y., Helentjaris T., Beatty M., Yang S., Smith H., Habben J., 2002: The use of gene expression profiling to dissect the stress sensitivity of reproductive development in maize. Field Crops Research, **75**, 111–121.

Živčák M., 2010: Účinok vysokých teplot, prejavy aklimačných mechanizmov a ich detekci na úrovni fotosyntetického aparátu bylín a drevín. In: Současné možnosti fyziologie a zemědělského výzkumu přispět k produkci rostlin (vybrané kapitoly), Výzkumný ústav rostlinné výroby, v.v.i., Praha, 155–173 (in Czech).