DOI: 10.2478/ahr-2021-0031
Acta hort regiotec, 24, 2021(2): 105–109

Research Article

Transpiration and water use efficiency of maize in different soil moisture conditions

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Article Details: Received: 2021-02-09 | Accepted: 2021-07-02 | Available online: 2021-11-30

Globally, agriculture accounts for 80–90% of the fresh water used by humans, and in many crop production systems; this water use is unsustainable. Irrigation of large areas of field and horticultural crops is impossible. Studies of the impact of drought on important field and horticultural crops are necessary to estimate dimensions of adaptation and mitigation measures to climate change. For this purpose, maize was monitored as a model crop in this study. In a three-year experiment (i) using the sap flow measurement method, the transpiration of maize was evaluated during flowering and grain filling, (ii) water use efficiency (WUE) was evaluated in four soil moisture conditions. The intensity of transpiration was closely correlated with the values of global radiation and vapor pressure deficit. However, soil water content was a major factor influencing transpiration under drought stress. The transpiration decreased when water content in the soil reached 28% of available water holding capacity (AWHC), but the yield of corn cobs decreased only under stress of 25% AWHC. Thus, the yield reacted less sensitively to lower water availability than transpiration. WUE increased with decreasing transpiration. Statistically significantly higher WUE was already observed at a water content of 42% AWHC, however, a higher WUE did not lead to a higher yield of corn cobs.

Keywords: sap flow, corn, WUE, drought, yield

1 Introduction

Currently, drought is the most significant environmental abiotic stress worldwide. The significance of drought increases with the time of its effect during the vegetation period and with its occurrence in the critical phases of the plants development. Canopy monitoring of meteorological elements is crucial for precise description of microclimatic conditions in the stand and their influence on plant physiological processes. Outcomes of microclimate monitoring provide valuable data for growth, phytopathology, yield and irrigation models, and wide range of other applications.

Changes in amount and distribution of precipitation can be expected in the future. As Spáčilová et al. (2014) proved in conditions of the Czech Republic, the number of days without precipitation may increase from the current 79.9 days to 141.6 days in the period 2071–2100. However, no significant decrease in the amount of precipitation per year is expected. The authors also predict an increase in the average sum of active temperatures above 10 °C for the Czech Republic from the current 2,717 °C to 3,732 °C. The predicted changes increase the evapotranspiration demands of the environment to which the stands will be exposed. A similar increase in the frequency of drought can be expected in the surrounding countries in the Central Europe.

For most plant species, the sufficient water supply in the soil is 45–75% of available water holding capacity (AWHC) of the soil. Nevertheless, it is different according to plant species and growth phase of the plant, whereas in the case of maize, the critical periods are flowering of both male and female inflorescences and the beginning of grain filling in terms of negative impact of water scarcity on grain yield (Çakir, 2004). The limit of transpiration sensitivity to the availability of soil water can also be influenced by a genotype (Klimešová et al., 2020).

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Transpiration intensity can be considered as an indicator of plant water status if the sap flow measurement is considered a suitable method for determining whole plant transpiration (Escalona et al., 2000) and drought stress monitoring (Gavloski et al., 1992). For practical purposes, determining the intensity of transpiration using the sap flow can be used to verify the dimensioning of irrigation.

The aim was (i) to study the response of maize plants to different levels of water supply, (ii) to determine the amount of water in the soil with an impact on transpiration, yield of corn cobs, harvest index, and water use efficiency (WUE).

2 Material and methods

The pot experiments were conducted in three years in „field" conditions in terms of natural day length, solar radiation, air speed, air temperature and humidity (Table 1), but with controlled irrigation. The observed part of the vegetation period (BBCH 61–87; (Meier, 1997)) was divided into periods according to the course of sap flow values, phenology of plants, and meteorological conditions.

The plants were maintained under four different irrigation regimes beginning at phase BBCH 50:

- condition A, the control, involved 80% of the AWHC,
- condition B, mild stress, at 42% AWHC,
- condition C, severe stress, at 28% AWHC,
- condition D, very severe stress, at 25% AWHC.

The experiment was conducted using the maize (*Zea mays* L.) genotype „2087", recommended as a drought-tolerant genotype. Six maize plants were planted in each container with a volume of 200 dm3 and dimensions of 0.73 × 0.54 × 0.51 m. Gleyic fluvisol with 49–58% of fine particles (<0.01 mm) was used as a substrate. Field water capacity of soil was 43.0 vol%, wilting point 20.8 vol%.

The cob yield and harvest index (HI) as well as the biomass yield and dry matter yield of whole plants were evaluated for all of the plants in each experimental treatment at the stage of full maturity (BBCH 89). The harvest index was calculated by dividing the dry weight of the cobs by the dry weight of the entire plant. The water-use efficiency of cob yield (WUEc) was calculated based on the amount of water consumed by the plant in a generative period (BBCH 61–87) and the cob yield: WUEc = dry matter yield of cobs per plant/sum of water transpired by the plant.

Transpiration was monitored through continuous measurements of xylem sap flow by EMS62 sap flow system (EMS Brno, Czech Republic), which uses the "stem heat balance" method (Kučera et al., 1977). The sap flow values (g.h^{-1}.plant^{-1}) were provided at 10-min intervals. Only diurnal sap flow values were included for the analyses. Two plants from each condition were measured between BBCH 61 and BBCH 87.

The relative air humidity (%), air temperature (°C) and global solar radiation (W.m^{-2}) were measured at 10-min intervals using Minikin sensors (EMS Brno, Czech Republic). The soil moisture content (%) was measured at 15-min intervals using VIRRIB automatic electromagnetic sensors (AMET Velké Bílovice, Czech Republic).

The experimental data were statistically analyzed using STATISTICA12 software (StatSoft Inc., Tulsa, USA). The analyses performed included variance analysis and the consequent testing using the Tukey's HSD 95% confidence test.

3 Results and discussion

3.1 Intensity of transpiration in different moisture conditions

Drought stress was manifested by a decrease in transpiration, which was significant during the flowering period and at the beginning of grain filling (BBCH 65–71), i.e. 1–2 weeks of stress. At this stage, the differences in transpiration between variants were the greatest.

The evaluation of the average sap flow of maize plants over the entire vegetation period in three years confirmed a statistically significant reduction of sap flow under the influence of drought stress (Fig. 1). Soil water content at 42% AWHC (condition B) did not cause a statistically

Table 1 Average daily values of global solar radiation and vapor pressure deficit in the bright part of the day in three years

Period	Growth stage (BBCH)	Days after sowing	Vapor pressure deficit (kPa)			Global solar radiation (W.m^{-2})		
			2012	2013	2014	2012	2013	2014
I	61–65	99	2.37	1.81	1.25	474	403	404
II	65–80	108	2.06	1.10	0.63	396	389	313
III	80–83	125	1.51	0.66	0.53	311	329	326
IV	83–87	144	×	0.31	1.05	×	274	425

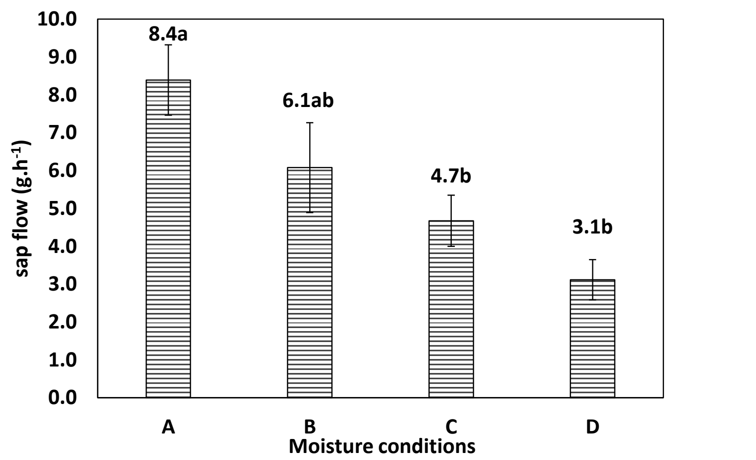

Figure 1 Sap flow of maize (g.h⁻¹.plant⁻¹). Average value for evaluated phases – BBCH 61–87
Data from a three-year observation. Statistically significant different means ($p \leq 0.05$) are indicated by different letters

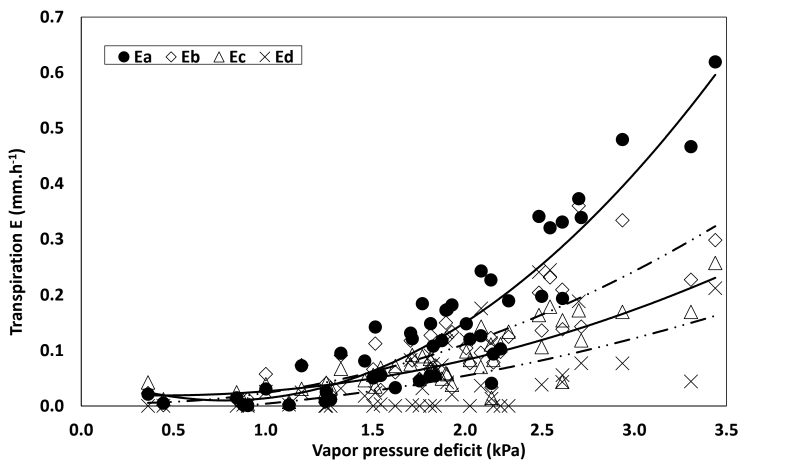

Figure 2 Relationship between vapor pressure deficit (kPa) and transpiration (mm.h^{-1}) in a daily step in four moisture conditions
A – Ea: $R^2 = 0.857$, B – Eb: $R^2 = 0.708$, C – Ec: $R^2 = 0.733$, D – Ed: $R^2 = 0.318$, year 2012

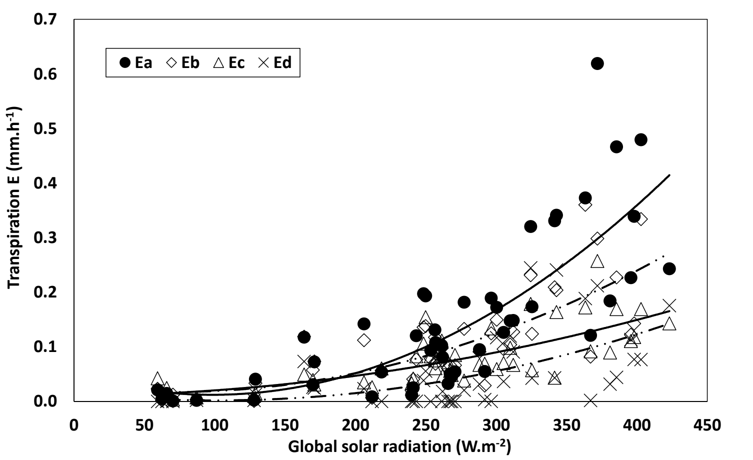

Figure 3 Relationship between global solar radiation (W.m^{-2}) and transpiration (mm.h^{-1}) in a daily step in four moisture conditions
A – Ea: $R^2 = 0.606$, B – Eb: $R^2 = 0.577$, C – Ec: $R^2 = 0.540$, D – Ed: $R^2 = 0.327$, year 2012

significant decrease of transpiration compared to the control (condition A). The soil water content at 25–28% AWHC (conditions C and D) reduced the transpiration of plants by 44–63% compared to the control. The limit of AWHC, which affects the intensity of transpiration, varies greatly. Vamerali et al. (2003) defined the soil AWHC limit 20% and 60% at which there was a significant reduction of transpiration depending on a genotype. Significant genotypic differences of maize in response to soil moisture availability were also observed in the experiment of Klimešová et al. (2020). The AWHC limit for statistically significant reduction of transpiration compared to control was 25–30% AWHC for a stress-tolerant genotype, 40% AWHC for a stress-sensitive genotype. Wu et al. (2011) observed a statistically significant decrease in transpiration of maize already when the soil AWHC was reduced to 80% AWHC. In the study of Matejka et al. (2005), the calculated evapotranspiration of maize stand was affected when the AWHC decreased to 58%.

In all three years, a significant dependence of transpiration on meteorological elements was observed, namely on global radiation and vapor pressure deficit (Fig. 2 and Fig. 3). This dependence was very close in case of well-watered plants (A) or under mild stress of drought (B). The dependence weakened with advancing plant senescence or under stronger drought stress (conditions C and D). This fully corresponds to the results of Cai et al. (2020), who showed a decrease of transpiration under drought stress in the reproductive phase of maize and its independence from the course of photosynthetically active radiation values. At high vapor pressure deficit values under conditions of sufficient water supply (A), no reduction in transpiration was observed due to the closure of stomata. The effect of water shortage was mainly reflected in the decrease of absolute transpiration values already in conditions of mild evapotranspiration requirements in the morning.

3.2 Cob yield and water use efficiency

Yield parameters of maize were influenced by the year, the intensity of stress, and also the interaction of year with intensity of stress (Table 2).

The year 2012 differed from 2013 and 2014 in high values of dry weight of biomass and stem. The weight of the cobs was statistically significantly higher in 2012 and 2014 compared to 2013. The comparable cob yield in these years is surprising, because the intensity of transpiration in 2014 was statistically significantly lower by 41%. The highest values of harvest index (HI = 0.34) were found, as well as higher values of water use efficiency (WUEc) in 2014. On the contrary, in 2013, when the lowest weight of cobs, weight of biomass dry matter and the lowest harvest index were achieved, the intensity of transpiration was highest.

Different irrigation regime affected some yield parameters. The effect of water shortage on dry weight of total biomass or stem biomass was not proven. This indicates a limited effect of drought stress in generative phase of growth.

As the availability of water in soil decreased, the weight of cobs and HI value decreased. Statistically significant differences were found between condition D (25% AWHC) and conditions A (80% AWHC) and B (42% AWHC). Statistically significant decrease in transpiration compared to the control was confirmed in conditions of severe (C) and very severe stress (D). The yield thus reacted less sensitively than transpiration to lower intensity of watering. Wu et al. (2011) point to the fact that dry weight of maize is less sensitive to different degrees of water scarcity compared to transpiration. They also compared cumulative values of maize transpiration over the entire growing season with amount of dry matter formed and found that at higher transpiration, the decrease in cumulative transpiration (from the elongation phase to ripeness) has no effect on dry matter reduction. Klocke et al. (2004) found that watering lower by 40% compared to the control caused only a 16% decrease in yield. Limited watering thus increases the efficiency of water use

Table 2 Effect of year, variants, and interactions of variant and year on yield parameters of maize (average value). Statistically significant different means ($p \leq 0.05$) are indicated by different letters

Year × condition		Dry matter yield (g.plant^{-1})	Cob yield (g.plant^{-1})	Dry matter yield of stover (g.plant^{-1})	Harvest index
2012	**A**	128 bc	40.9 b	87.3 cd	0.31 abc
	B	127 bc	44.3 b	82.3 bcd	0.34 bc
	C	132 c	44.8 b	87.5 cd	0.34 bc
	D	103 abc	4.1 a	99.2 d	0.04 a
2013	**A**	69 a	15.2 ab	53.9 ab	0.22 abc
	B	75 a	21.1 ab	53.7 b	0.28 ab
	C	76 a	12.2 ab	63.9 abc	0.15 ab
	D	71 a	13.4 ab	57.3 abc	0.17 ab
2014	**A**	89 abc	34.5 ab	54.9 ab	0.38 bc
	B	89 abc	41.6 b	47.5 a	0.46 c
	C	85 ab	29.8 ab	49.0 a	0.30 abc
	D	64 a	18.3 ab	45.6 a	0.22 abc
Year					
2012		123 b	33.6 b	89.1 b	0.26 ab
2013		73 a	15.5 a	57.2 a	0.20 a
2014		82 a	31.1 b	49.3 a	0.34 b
Condition					
A		96 a	30.2 b	65.4 a	0.30 b
B		97 a	35.7 b	61.2 a	0.36 b
C		98 a	28.9 b	66.8 a	0.26 ab
D		79 a	11.9 a	67.3 a	0.14 a

(WUE) by plants due to a greater reduction in water use compared to yield (Djaman & Irmak, 2012).

Water use efficiency for cobs (WUEc) was influenced by the year. The reason for different values of WUEc could be the course of global radiation values and especially the vapor pressure deficit. In 2014, by 60% lower values of vapor pressure deficit were found compared to 2012, which supported higher WUEc. Lower VPD may be associated with higher WUE values for maize (Tallec et al., 2013). Lower WUEc was repeatedly observed in conditions without drought stress, in the control. It increased with the strength of stress (conditions B, C), but decreased again under severe drought stress (condition D). Thus, with the amount of consumed water, the efficiency of its use decreased. Moderate drought stress limits transpiration due to partial stomata closing, while the assimilation of the CO_2 continues, which basically leads to WUE increase (Chaves et al., 2010). Limited watering thus increases WUE due to a greater reduction in water consumption than in yield (Djaman & Irmak, 2012). However, under severe stress, growth is already significantly reduced, so the WUE value decreases (Farooq et al., 2009).

4 Conclusions

Soil water content was the main factor influencing the transpiration under the influence of medium to severe water shortage. Yield responded less sensitively to lower watering intensity than the transpiration. WUEc decreased with increasing amount of water consumed. The limit of soil water content, at which there was a decrease in transpiration and yield, was at the level of severe drought stress (25% of AWHC). Prediction of maize biomass yield during dry periods is quite problematic. The relationship between the amount of maize biomass and moisture conditions is not definitely linear.

Acknowledgments

This research was supported by the Ministry of Agriculture of the Czech Republic (National Agency of Agricultural Research Ministry of Agriculture of the Czech Republic) project No. QK1920280 „Innovation of the Evaluated Soil-Ecological Units (BPEJ) for state administration needs".

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