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Water demands and biomass production of sorghum and maize plants in areas with insufficient precipitation in Central Europe

Michaela ŠKEŘÍKOVÁ[1,*], Václav BRANT[1], Milan KROULÍK[2], Jan PIVEC[1], Petr ZÁBRANSKÝ[1], Josef HAKL[1], Michael HOFBAUER[1]

[1]*Faculty of Agrobiology, Food, and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic*
[2]*Faculty of Engineering, Czech University of Life Sciences Prague, Prague, Czech Republic*
**Corresponding author: skerikovam@af.czu.cz*

ABSTRACT

Škeříková M., Brant V., Kroulík M., Pivec J., Zábranský P., Hakl J., Hofbauer M. (2018): Water demands and biomass production of sorghum and maize plants in areas with insufficient precipitation in Central Europe. Plant Soil Environ., 64: 367–378.

Evapotranspiration and transpiration measurements represent a tool for the assessment of crop water demand. The aim of this study was to compare sorghum and maize with respect to its potential for forage production in areas with insufficient precipitation in Central Europe. The values of the actual evapotranspiration (ET_a, Bowen ratio balance method), transpiration (sap flow method), leaf area index (LAI) and biomass production of sorghum and maize were measured continuously in years 2010–2012. Sorghum stand provided higher ET_a in comparison with maize in dry year 2012. Maize produced consistently more above-ground biomass yield and lower LAI over all evaluated years than sorghum. The sorghum provided similar or higher water use efficiency (WUE) than maize during the period of intensive prolongation growth, however, the higher WUE did not result in higher biomass production.

Keywords: *Sorghum bicolor* L. Moench; *Zea mays* L.; water stress; arid area; rainfall

Sorghum (*Sorghum bicolor* L. Moench) might be an alternative for maize (*Zea mays* L.) in the arid areas. Water stress strongly reduced the yield of maize (Ort and Long 2014, Lobell et al. 2014) whereas higher resistance of sorghum to water stress has been documented by Rosenow et al. (1983) and Schittenhelm and Schroetter (2014). Sorghum produces comparable biomass to maize when water is the limiting factor (Rooney et al. 2007, Zegada-Lizarazu et al. 2012).

In Central Europe, the sowing date of sorghum is postponed from the maize by 14 to 25 days because of higher requirement on soil temperature (Brant et al. 2011). This delay leads to shorter vegetation and it can affect the overall water consumption of sorghum in contrast to maize. Later sorghum sowing date is associated with a delay in crop maturing, which can be a reason for higher sorghum water consumption before harvest. Moroke et al. (2005) described that the sorghum delay in maturing, compared to sunflower, contributed to higher sorghum water uptake at the end of its vegetation.

Tolk and Howell (2003) reported lower water consumption of sorghum in mild climatic conditions in comparison with arid areas. In humid years, evapotranspiration of sorghum canopy was higher than in maize, however, an opposite effect was observed in normal and dry years (Pan et al. 2011). Howell et al. (1994) published higher values of seasonal evapotranspiration of irrigated maize in contrast to sorghum canopies.

Bowen ratio balance method (BREB) represents one of the methods for the assessment of actual evapotranspiration. The use of the sap flow method

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for measuring of water flow was reported for maize (Cohen et al. 1990, Gavloski et al. 1992, Bethenod et al. 2000) and for sorghum (Zhang and Kirkham 1995). A positive correlation between evapotranspiration values of maize determined by BREB and sap flow was documented (Bethenod et al. 2000). This study also showed that the difference between sap flow and evapotranspiration might be less than 10% on dry soils, probably due to low evaporation. Evaporation depends on crop leaf area index (LAI). A negative correlation between actual evaporation and LAI of sorghum was reported by Kato and Kamichika (2006).

Values of the actual evapotranspiration and the amount of plant biomass are the input variables for water use efficiency (WUE) determination. In the previous studies, WUE values for sorghum ranged from 1.0–7.4 g/L in field conditions (Garofalo and Rinaldi 2013, Hao et al. 2014, Yimam et al. 2015). It can be summarized that growing of sorghum can provide lower water consumption and more favourable WUE in comparison with maize where values ranging from 1.12–1.66 g/L were reported by Sun et al. (2010). However, these benefits must be verified in the particular environment.

The aim of this paper was to compare the water consumption of sorghum and maize in association with above-ground biomass production in areas with low annual precipitation.

MATERIAL AND METHODS

Field experiments were conducted in years 2010–2012 in Central Bohemia in Budihostice (50°18'23.499''N, 14°15'28.893''E, 210 m a.s.l.) where soil type is Haplic Chernozem. The ratio between the total amount of precipitation and potential evapotranspiration is 0.7–0.8 in this locality (Pivec et al. 2006). Measurements of actual evapotranspiration, transpiration, above-ground biomass production, leaf area index and water utilization rates for maize and sorghum crops were carried out in field conditions. The size of the experimental plots was 1.5 ha (square 122.5 × 122.5 m, the measuring equipment was placed in the middle of the plot). Cereals were a previous crop. After the autumn ploughing, 46 kg N per hectare was applied under seedbed layer before seeding. The following seeding dates of the maize were used: April 21 in 2010 (represents 111 day of the year – DOY) with cv. Kuxxar (Syngenta International AG), April 7 in 2011 (97 DOY, cv. PR38N86 – Pioneer Hi-Bred Northern Europe Sales Division GmbH) and April 21 in 2012 (112 DOY, cv. PR38N86). The sorghum seeding dates correspond with May 17 (137 DOY), May 9 (129 DOY) and May 11 (132 DOY). The cv. Sucrosorgo 506 (Syngenta International AG) was sown in all years. Row spacing was 0.75 m for both crops. The numbers of plants per unit area 30 days after sowing were determined (Table 1).

Canopy parameters. Dry above-ground biomass production and LAI values were measured regularly. Using the number of plants per unit area (Table 1), the measured biomass production (B_m, t/ha) and measured leaf area index (LAI_m) values per unit area were determined. The values B_m were used to calculate the daily values of dry above-ground biomass production (B_{calc}, t/ha). The average plant weight was always determined from 20 plants at dry biomass basis. The biomass was dried at 105°C to the constant weight. Leaf area per plant determination was based on infrared image analysis (Brant et al. 2017). Computational algorithms for B_{calc} and LAI_{calc} calculation follow Brant et al. (2017), where parameters of equations are documented in Tables 2 and 3.

Evapotranspiration measurement. The Bowen's ratio energy balance was used to determine the actual evapotranspiration values. Calculation of Bowen's ratio is based on the assumption that equal values of the apparent and latent heat coefficients are the same, and then it is possible to determine the ratio of apparent and latent heat by measuring the temperature and humidity gradients above the transpiring surface (Woodward and Sheehy 1983). In this experiment, the radiation balance was measured by the Schenk balance meter (Wien, Austria).

Table 1. Average plant density of maize and sorghum in 2010–2012

Species	Number of plants per ha		
	2010	2011	2012
Zea mays	95 586[a]	86 897[a]	89 333[a]
Sorghum bicolor	160 000[c]	128 276[b]	108 667[a]

Number of plants was determined 30 days after sowing. Different letters document significant differences between years within each row (Tukey's *HSD* (honestly significant difference), α = 0.05)

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Table 2. Equation parameters for calculation of maize and sorghum biomass production (B_{calc}, t/ha) according to B_{calc} = par1/(1 + exp(–(DOY – par2) × par3)) – par4

	Plant	Par1	Par2	Par3	Par4	Correlation index	Number of variable
2010	*Zea mays*	21.69	200.93	0.07	0.27	0.998	15
	Sorghum bicolor	22.55	211.87	0.08	0.43	0.998	12
2011	*Z. mays*	25.71	202.96	0.06	0.49	0.994	19
	S. bicolor	16.34	204.08	0.09	0.17	0.997	16
2012	*Z. mays*	24.31	205.97	0.06	0.49	0.996	18
	S. bicolor	25.23	220.33	0.06	0.62	0.998	15

DOY – day of the year

The radiation balance values were adjusted by the energy amount flowing from the active plant cover (Allen et al. 1998) into the soil. The heat flow to the soil was measured by the Huxeflux sensor (Delft, the Netherlands). The values of the actual evapotranspiration (ET_{am}) (mm/h in 10 min measured interval) were obtained within the measurement. Missing values of the ET_{am} values were supplemented with potential evapotranspiration values (ET_0, mm/h, mean calculated over 10 min interval), according to the methodology by Zábranský et al. (2015). ET_0 values were calculated according to Allen et al. (1998).

The BREB systems (EMS, Brno, Czech Republic), which was placed in the centre of the experimental area, were used. The Decagon 10HS (Decagon Devices, Inc., Pullman, USA) sensors were used for volumetric water content (VWC, %) determination at a depth of 30 cm (recording interval 10 min). Evapotranspiration measurement was realized at the DOY interval of 160–257 for maize and 160–253 for sorghum in 2010, 167–249 DOY for maize and sorghum in 2011 and 155–237 DOY for maize and 180–240 DOY for sorghum in 2012.

Transpiration measurement. The so-called sap flow measurement is based on the temperature balance between the heat input and the temperature increase in the defined space (Kučera et al. 1977, Tatarinov et al. 2005). The sap flow values (Q_m, kg/h) were measured with a 12 channel T4.2 sap flow meter (EMS, Brno, Czech Republic) and were recorded at 10 min intervals throughout the measurement period. Missing values of Q_m were replaced by calculated values (Q_{calc}, algorithm 1). Sap flow data were processed by Mini32, ver. 4.2.31.0 software (EMS, Brno, Czech Republic) based on the equation described by Pivec et al. (2011):

$$Q_{calc} = \text{par1}\frac{R_g}{(R_g + \text{par2})}\frac{\text{VPD}}{(\text{VPD} + \text{par3})} \quad (1)$$

Where: R_g – global solar radiation (W/m^2); VPD – vapour pressure deficit (hPa). The parameters (par) 1–3 were determined for the whole measurement period. Calculation of the vapour pressure saturation follows Tetens (1930). Q_{calc} values were calculated from the measured data (collected at 10 min interval) for the whole measurement period.

Table 3. Equation parameters for calculation of maize and sorghum leaf area index (LAI_{calc}) according to LAI_{calc} = par1/(1 + exp(–(DOY – par2) × par3)) – par4

	Plant	Par1	Par2	Par3	Par4	Correlation index	Number of variable
2010	*Zea mays*	4.46	172.86	0.15	0.02	0.998	6
	Sorghum bicolor	9.33	194.60	0.13	0.05	1.000	6
2011	*Z. mays*	4.75	172.96	0.27	–0.24	0.993	7
	S. bicolor	6.34	179.70	0.15	0.05	0.990	7
2012	*Z. mays*	3.59	168.89	0.20	–0.14	0.966	10
	S. bicolor	7.73	183.64	0.27	–0.06	0.999	8

DOY – day of the year

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Table 4. Linear estimation of maize and sorghum transpiration (Q, mm/day) based on the actual evapotranspiration (ET_a, mm/day) in evaluated years

Period	Plant	Model
2010	*Zea mays*	$Q = -1.1644 + 1.0066 \times ET_a$, $r = 0.893$, $n = 50$, confidence level = 99%
	Sorghum bicolor	$Q = -1.6701 + 2.2610 \times ET_a$, $r = 0.939$, $n = 26$, confidence level = 99%
2011	*Z. mays*	$Q = -1.2287 + 1.6448 \times ET_a$, $r = 0.921$, $n = 53$, confidence level = 99%
	S. bicolor	$Q = -1.8506 + 2.4507 \times ET_a$, $r = 0.896$, $n = 23$, confidence level = 99%
2012	*Z. mays*	$Q = -1.3388 + 1.6032 \times ET_a$, $r = 0.778$, $n = 25$, confidence level = 99%

r – correlation coefficient; *n* – number of variable

The Q (kg/h) values were determined after replacing the missing Q_m (kg/h) values by Q_{calc} (kg/h), in line with Brant et al. (2012) (Table 4).

Sap flow values were measured in 204–252 DOY interval in 2010 (maize and sorghum) and in 195–249 DOY (maize) and 224–249 DOY (sorghum) in 2011. In 2012, only data from maize measurement (204–252 DOY) are available because sorghum sap flow sensors were damaged by rodents. Q_m values were always measured on at least 9 plants of the evaluated crop. Transpiration (T_r, mm/day) was determined as average of multiples Q (kg/day) of plant and plant number per unit area (Table 1). The T_r values were visualised as the range of the measured Tr_i values for evaluated stands ± standard deviation (SD). The relevance of the T_r values (mm/day) of the individual plants was verified based on the determination of the amount of energy for the perfused amount of water in relation to the daily amount of radiation (Rn, MJ/m^2). Specific evaporation heat values (λ, J/g) were determined according to the Hooghart (1971) algorithm.

Water use efficiency determination. WUE values were determined as a proportion of dry above-ground biomass and actual evapotranspiration of the stand. Average daily WUE values were calculated from daily ET_a values (kg/m^2) and daily biomass increments gains B_{calc} (g/m^2). WUE (g/kg) values were set for days when the daily sum of R_g was ≥ 18 MJ/m^2. The reason for that was to determine the WUE values

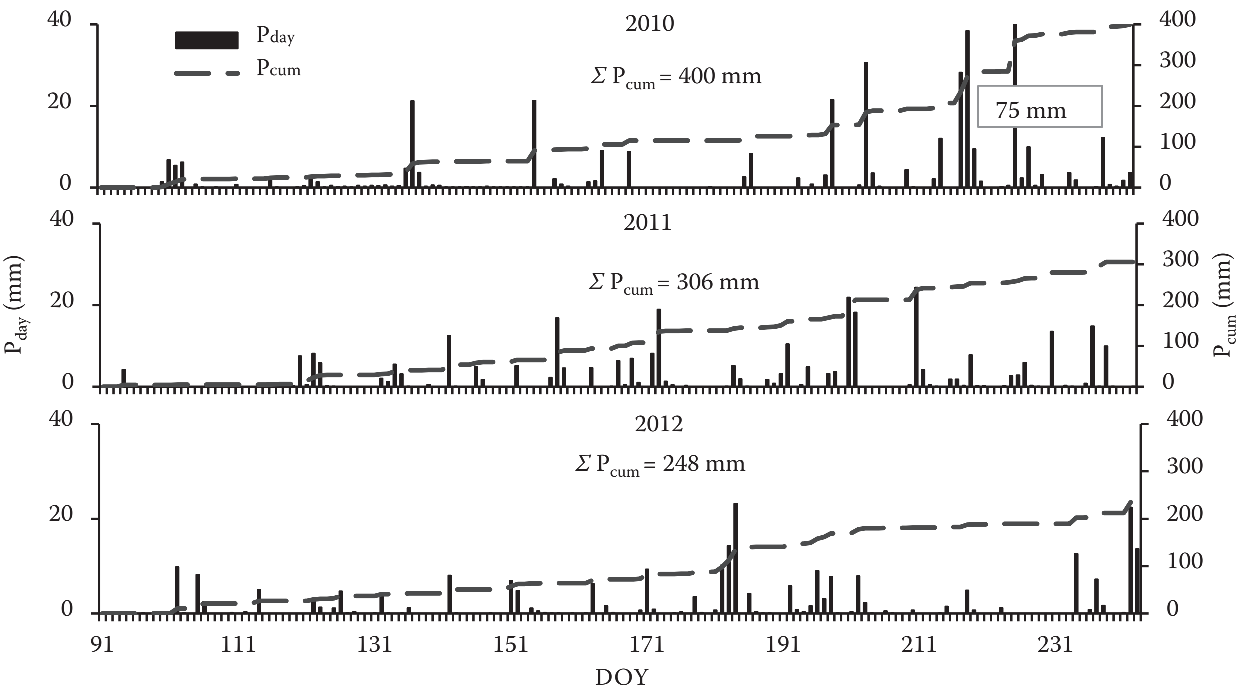

Figure 1. Daily sums of precipitation (P_{day}) and cumulative precipitation over the growing period (P_{cum}) in years 2010–2012. DOY – day of the year

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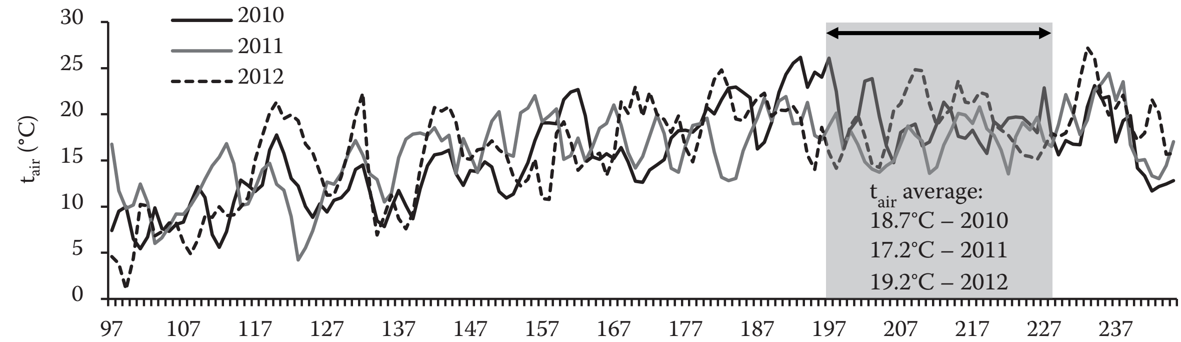

Figure 2. Daily means of temperatures (t_{air}) over the period of intensive biomass accumulation (200–230 DOY) in years 2010–2012. DOY – day of the year

only under suitable evapotranspiration conditions that were determined based on Rg inputs.

Precipitation (P, mm) and air temperature (T_{air}, °C) were taken from the weather station located at the Budihostice experimental field (http://www.emsbrno.cz/p.axd/cs/Lokality.CZUFAPPZ.html). Daily sums of precipitation and means of temperature are shown in Figures 1 and 2. Calculations of ET_{am} (mm/h), ET_0 (mm/h) and ET_a (mm/day) were performed using the software Mini 32, ver. 402.75 (EMS, Brno, Czech republic) and regression analysis and ANOVA (Tukey's *HSD* (honestly significant difference) test, α = 0.05) were performed using the programme Statgraphics ® Plus, ver. 4.0 (The Plains, USA).

RESULTS AND DISCUSSION

Canopy parameters. Figure 3 documents the daily dynamics of dry above-ground biomass produc-

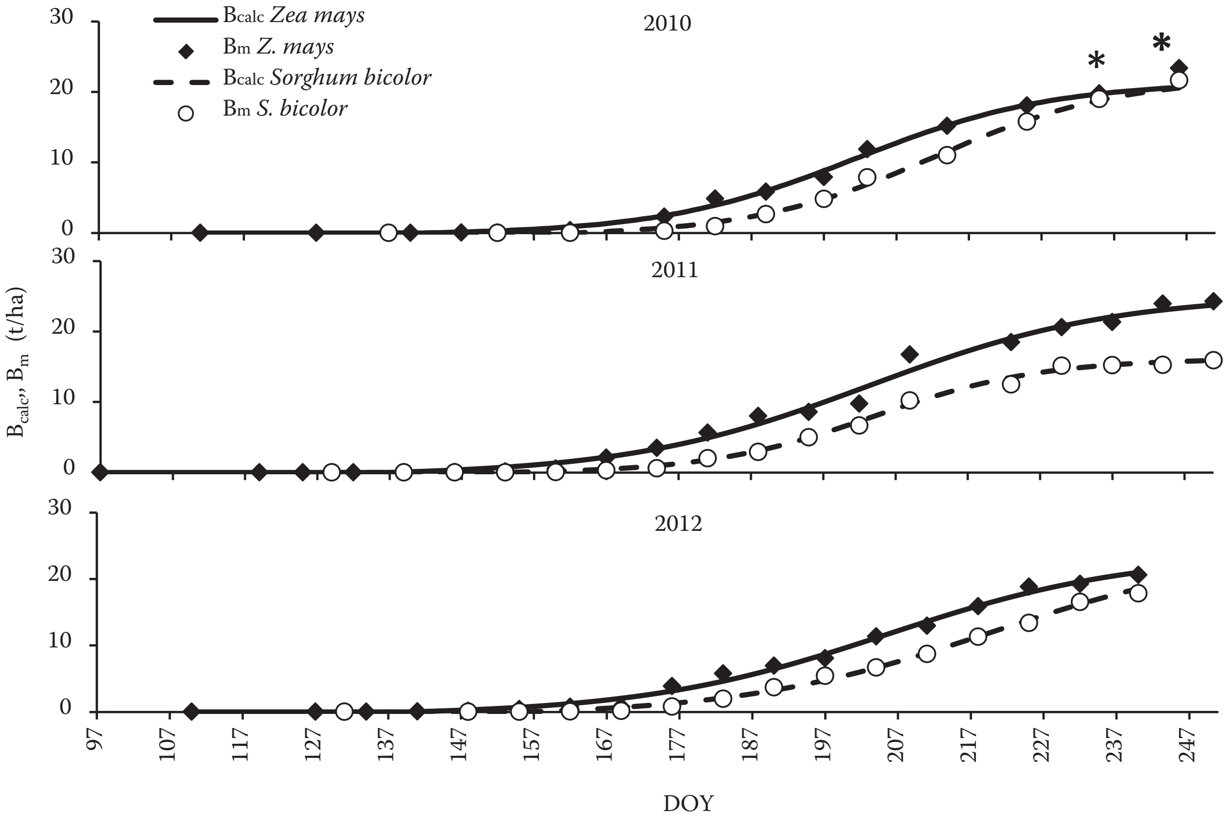

Figure 3. The dynamics of maize and sorghum above-ground biomass production (t/ha) in years 2010–2012. The points represent the measured values (B_m) and curves were fitted by the calculated value (B_{calc}, t/ha). Asterisks indicate values with non-significant differences in B_m between species (Tukey's *HSD*, α = 0.05). DOY – day of the year

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tion (B_m and B_{calc}) of maize and sorghum in years 2010–2012. Higher production was established for maize in all evaluated years. The harvested maize dry matter forage yields were 23.4 t/ha (2010), 24.3 t/ha (2011) and 20.6 t/ha (2012). Sorghum provided forage yield of 21.7 t/ha (2010), 15.7 t/ha (2011) and 17.8 t/ha (2012). The most intensive biomass accumulation occurred between 200–230 DOY. The weight of the cobs represents over 50% of maize above-ground biomass (Fuksa et al. 2004). Limited formation of generative organs in sorghum were observed where their proportion reached an average 40% of the plant biomass, which resulted in lower dry matter content (17.9%, mean 2010–2012) in contrast to maize (29.6%). Hermuth and Kosová (2017) highlighted the importance of utilization of sorghum cultivars adapted to local environment, e.g., the first Czech sorghum cv. Ruzrok, enabling mature seed production in the temperate climate of Central Europe.

Sorghum lower dry matter is in line with the results of Schittenhelm and Schroetter (2014). Larger harvest values of LAI_m and LAI_{calc} were found in sorghum stands (Figure 4). The values of LAI_m for maize 4.1 (2010), 4.7 (2011) and 2.6 (2012) whereas sorghum LAI_m 9.3, 5.6 and 7.7 (2010, 2011 and 2012, respectively) were observed. For maize, the usual values of LAI are within 2.6–4.8 m (Timlin et al. 2014, Saseendran et al. 2015).

Meteorological characteristic. The highest sum of precipitation (400 mm) within 91–243 DOY was observed in year 2010. The lowest sum of precipitation over the vegetation period was observed in 2012 (248 mm) and 306 mm was detected in 2011. Year 2012 was characterized by low values of daily sum of precipitation, mostly under 10 mm per day (Figure 1). A lower effect on the increase of soil water supply can be expected under this sum of precipitations due to evaporation.

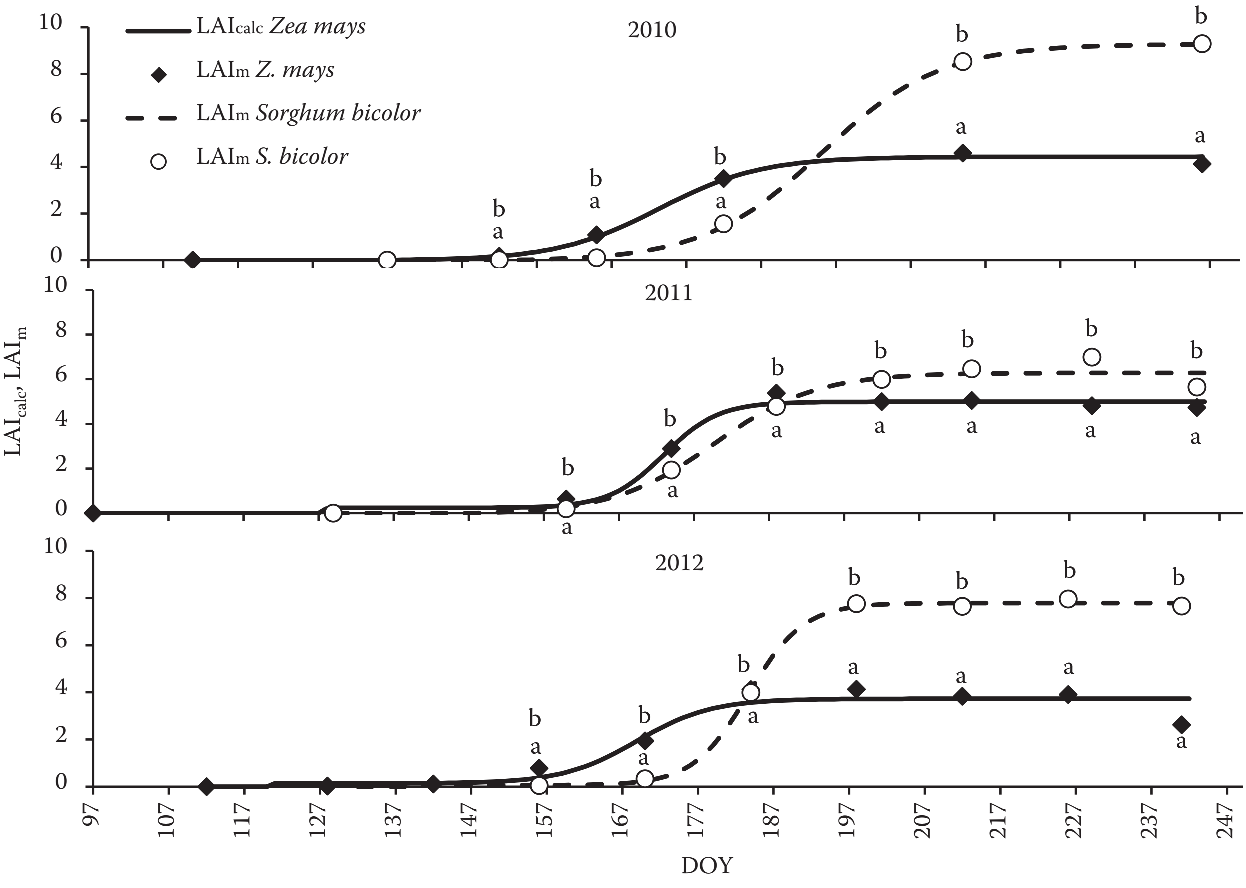

Figure 4. Dynamics of maize and sorghum leaf area index (LAI) development in years 2010–2012. The points represent the measured values (LAI_m) and curves were fitted by the calculated value (LAI_{calc}). Different letters document significant differences of LAI_m between species within the date of sampling (Tukey's *HSD*, α = 0.05). DOY – day of the year

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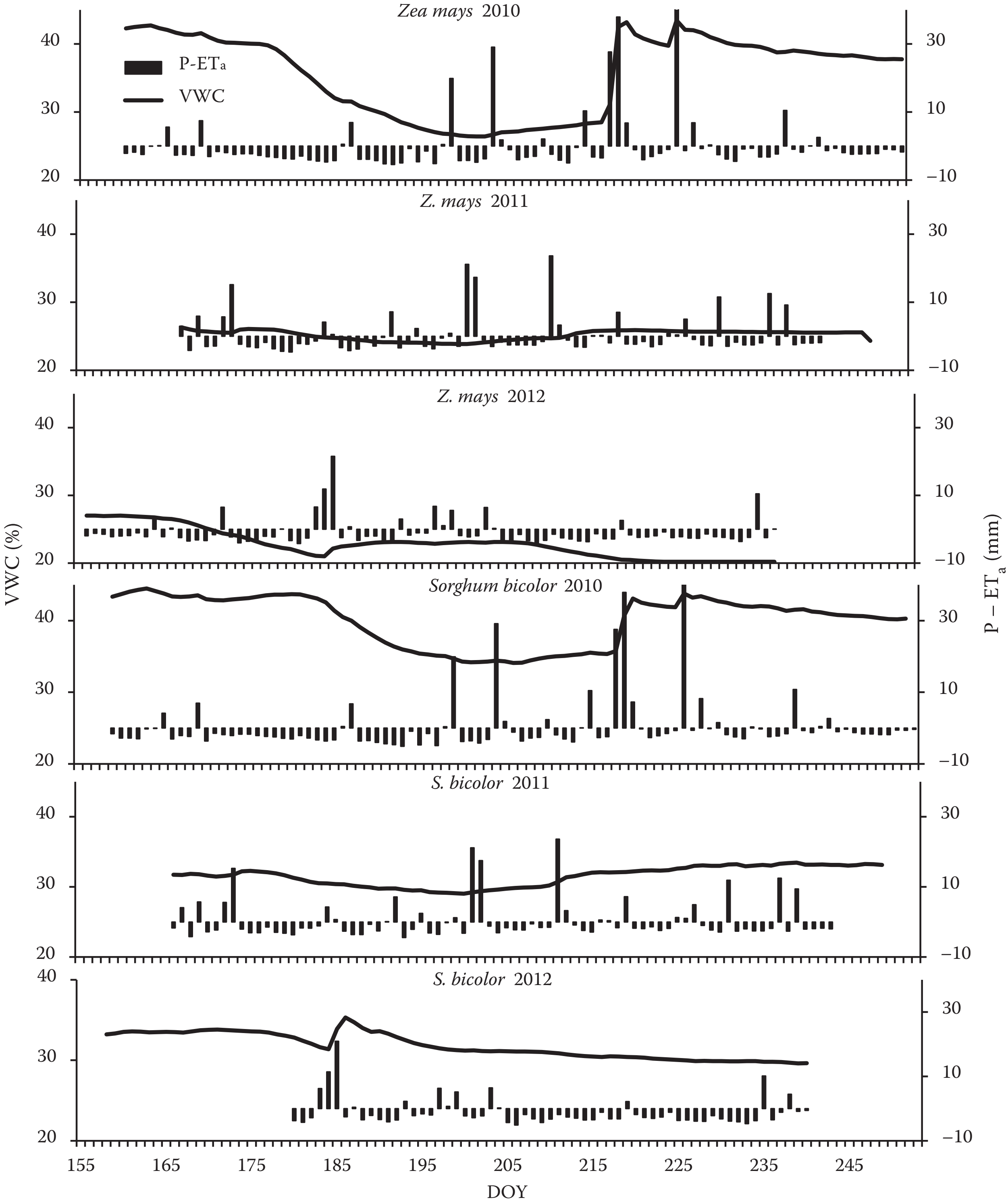

Figure 5. Relationship between daily sum of precipitations (P, mm/day), daily values of actual evapotranspiration (ET_a, mm/day) and daily soil moisture (VWC, %) for maize and sorghum in years 2010–2012. DOY – day of the year

The differences between daily sum of precipitation (P, mm/day), actual evapotranspiration values (ET_a, mm/day) and volumetric water content (VWC, %) at 30 cm depth during the evaluated years are shown in Figure 5. The VWC values were lower for maize plots in all years of evaluation. Greater decreases in VWC values in maize stands could also be caused by earlier sowing and associated with subsequent earlier water consumption for crop transpiration. Kato and Kamichika

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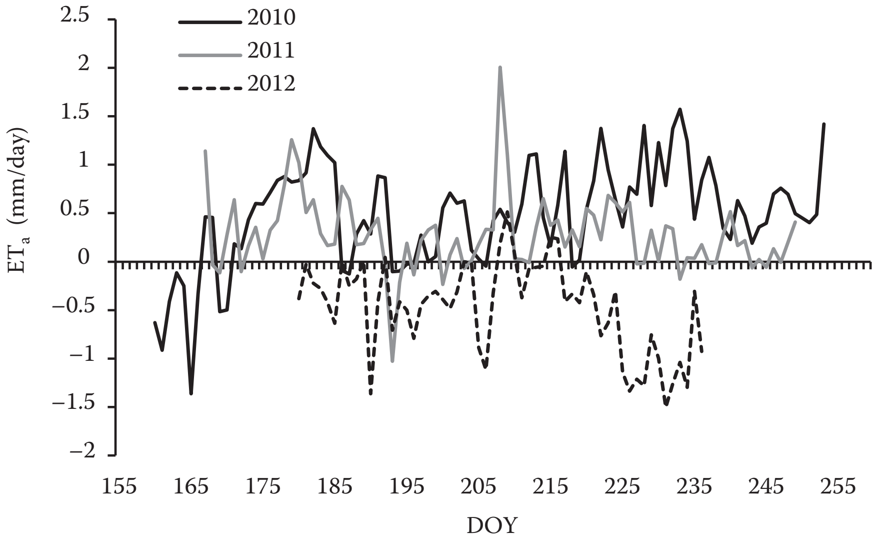

Figure 6. Differences in daily values of actual evapotranspiration (ET_a) for maize and sorghum in years 2010–2012. DOY – day of the year

(2006) proposed a decrease in evaporation due to a higher LAI values as explanation for higher VWC values in plot with sorghum. Sorghum intensive leaf formation was initiated around 180 DOY (Figure 4). Another explanation could be lower sorghum water consumption in contrast to maize (Tolk and Howell 2003).

The average daily air temperature for the period 91–243 DOY was 16.5°C in 2012, 15.6°C in 2010 and 16.1°C in 2011. As shown in Figure 2, in the period of intensive biomass accumulation (200–230 DOY), the highest average air temperature was detected in 2012 (19.2°C), in 2010 (18.7°C) and in 2011 (17.2°C).

Stand water demand. Maize stands provided higher ET_a in comparison with sorghum (Figure 6) in 2010 and 2011. The daily average differences of maize ET_a were higher by 0.59 and 0.29 mm/day within the period of 180–235 DOY in 2010 and 2011, respectively. Measured ET_a values were 3.23 and 2.48 mm in 2010, 2.41 and 2.12 mm in 2011 for maize and sorghum, respectively. In dry year 2012, the maize daily ET_a was by about 0.46 mm/day lower in comparison with sorghum between 180–235 DOY (Figure 6). The average daily ET_a in the period was 2.72 mm for maize and 3.18 mm for sorghum.

In dry year 2012, higher sorghum ET_a could be associated with its higher water stress resistance (Sanchez-Diaz and Kramer 1971). This year also showed higher values of air temperature over crop growth compared to 2010 and 2011. According to Downes (1970), the sorghum transpiration rate accelerates with increasing air temperature. This relationship is also consistent with Tolk and Howell (2003), who reported higher sorghum water consumption in the areas with high evapotranspiration demand.

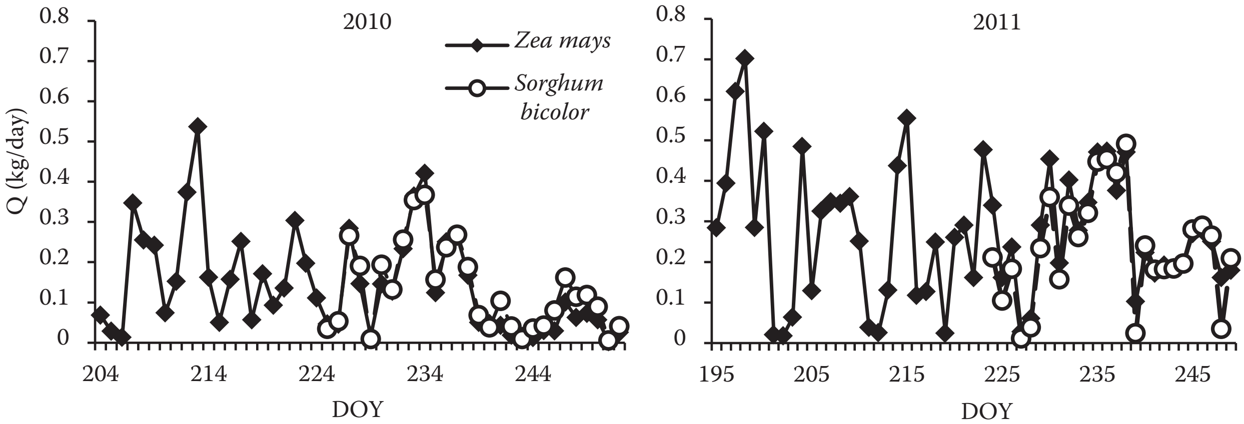

Figure 7. Average daily sap flow values (Q) per plant of maize and sorghum in years 2010–2011. DOY – day of the year

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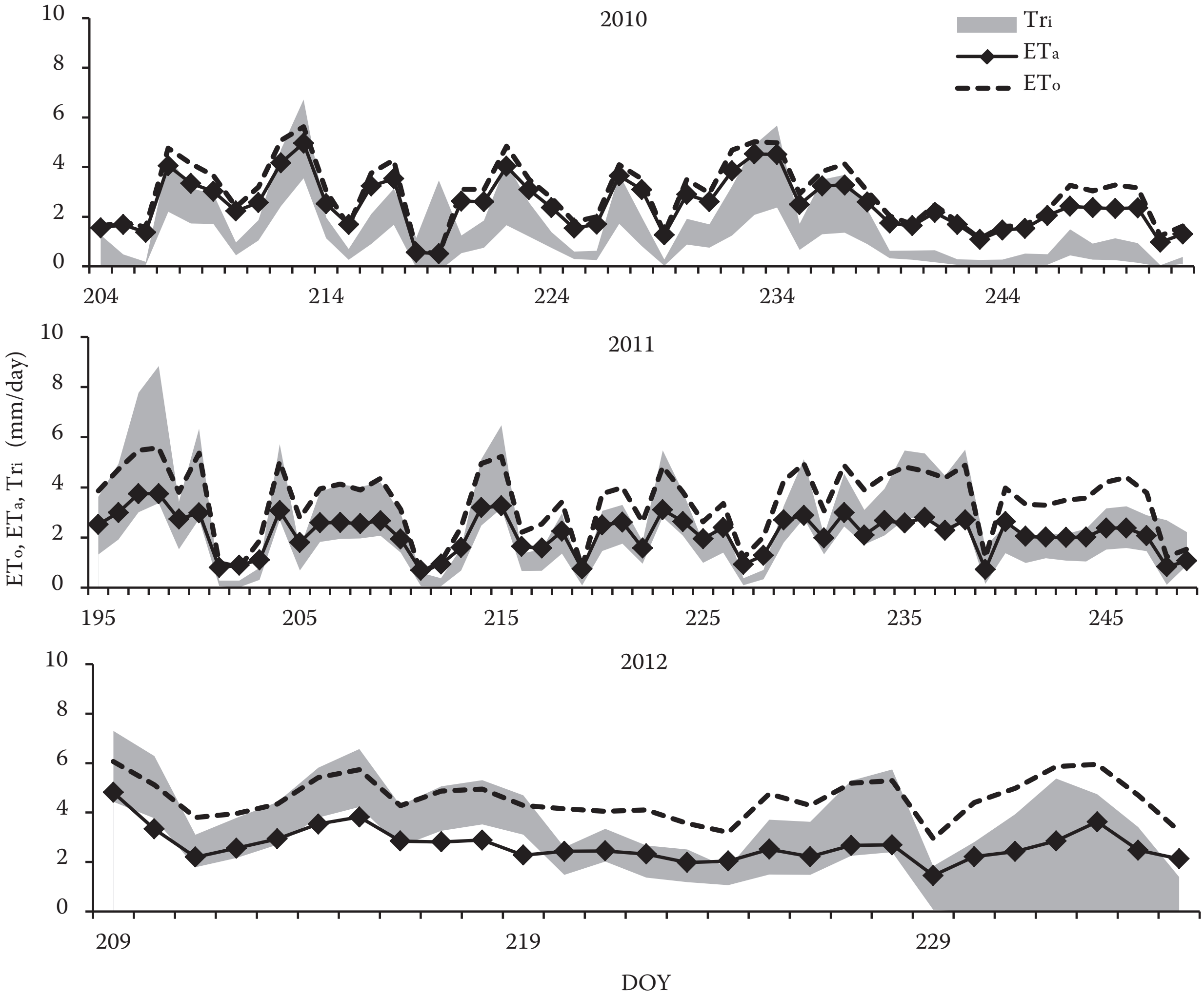

Figure 8. Daily maize values of potential evapotranspiration (ET_0) or actual evapotranspiration (ET_a) and daily transpiration (Tr_i) in years 2010–2012. Tr_i values (gray field) represent the range for evaluated stands using the mean of T_r ± standard deviation. DOY – day of the year

Average sap flow values were not significantly different between maize and sorghum in 2010 and 2011 (Figure 7). The number of plants per unit area had a major impact on the Q value of the stands. The high variability of sap flow values among the individual plants makes complicated the estimation of values per area unit. In our experiment, sap flow values ranged from 24 to 213 g/h per plant for maize whereas the values from 34 to 160 g/h were measured for sorghum. Gavloski et al. (1992) reported maize sap flow values from 32 to 122 g/h depending on the water regime. Maximal maize sap flow values could reach 150–175 g/h (Gavloski et al. 1992, Kjelgaard et al. 1997).

Figures 8 and 9 present daily values of actual evapotranspiration (ET_a, mm/day) and transpiration (Tr_i, mm/day) in 2010–2012. The maize transpiration more closely corresponds with the values of the actual evapotranspiration (Figure 8). Daily ET_a of sorghum was related to the lower limit of Tr_i interval. It suggests that lower evaporation of sorghum can be expected due to higher leaf coverage of soil expressed as LAI (Figure 4). This assumption is supported by the results of Kato and Kamichika (2006).

Water use efficiency. The values of WUE over 2010–2012 are presented in Figure 10. There was a clear trend for a value increase between 170–220 DOY, followed by a decline in the subsequent period. During the first period, biomass production strongly increased (Figure 3). In 2010, the highest WUE of maize reached 9.49 g/kg whilst 17.86 g/kg was observed for sorghum (180–240 DOY). Similarly, in 2011, the maize WUE was 14.45 g/kg and sorghum reached 15.41 g/

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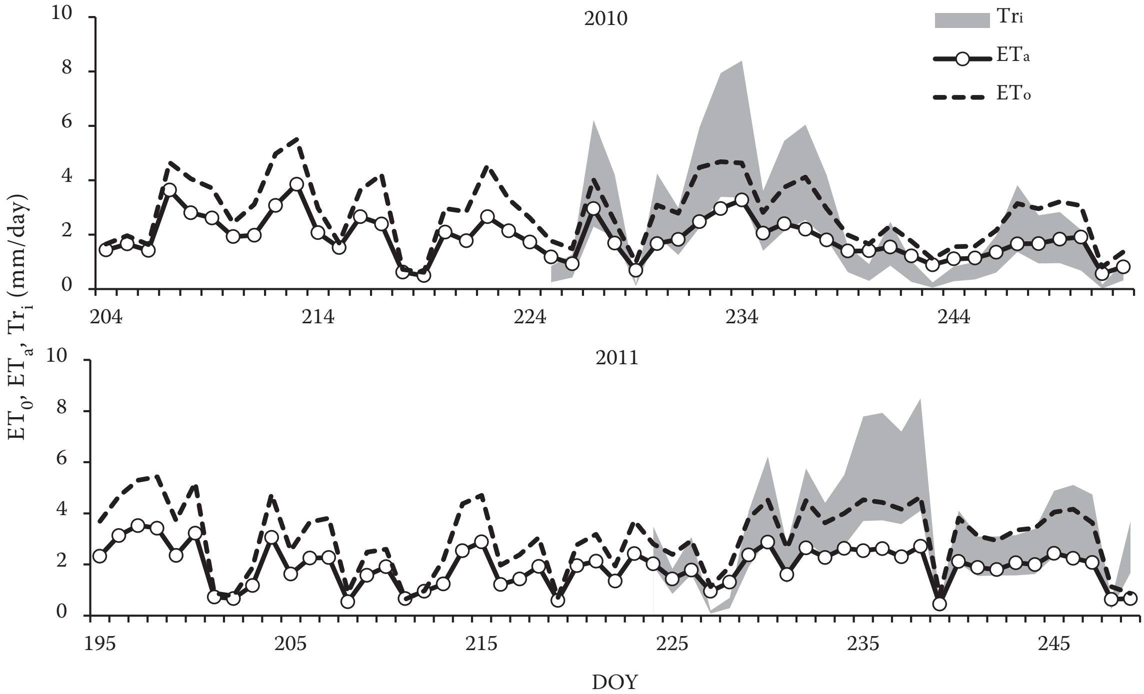

Figure 9. Daily sorghum values of potential evapotranspiration (ET_0) or actual evapotranspiration (ET_a) and daily transpiration (Tr_i) in years 2010–2012. Tr_i values (gray field) represent the range for evaluated stands using the mean of T_r ± standard deviation. DOY – day of the year

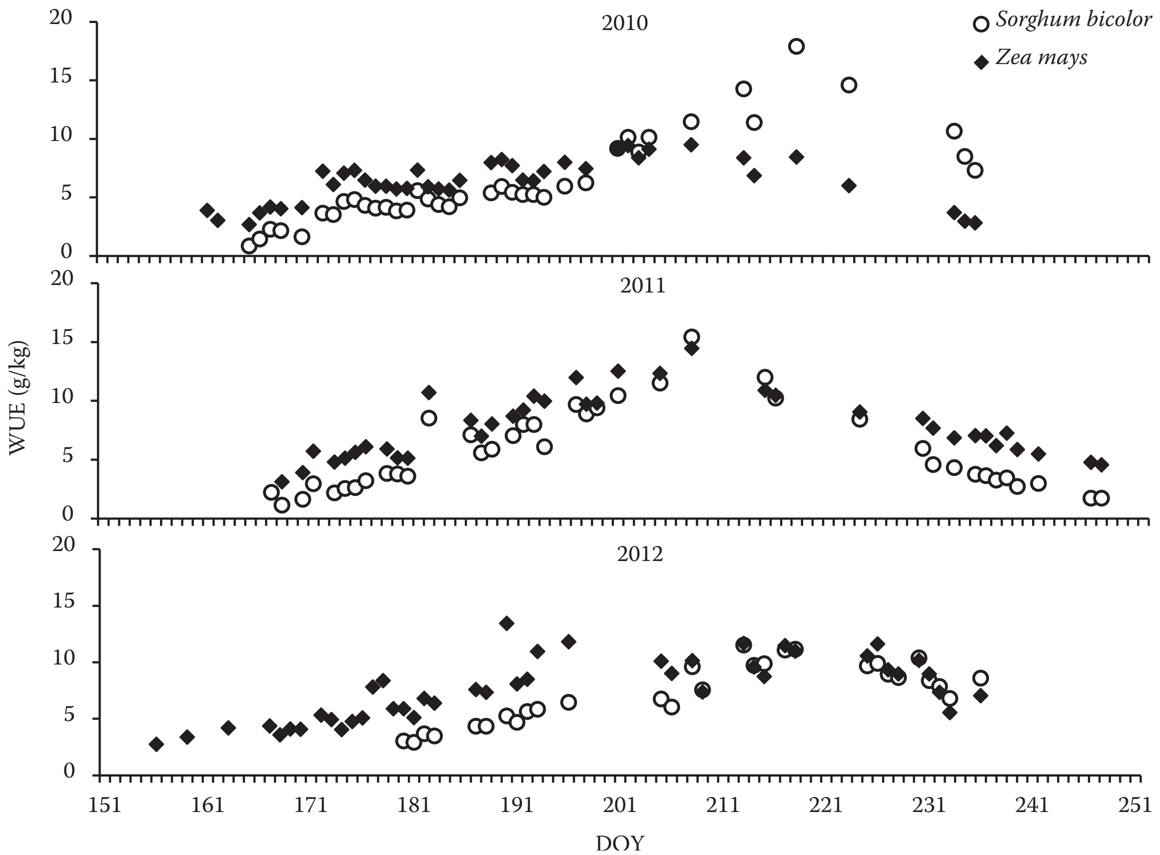

Figure 10. Average daily values of water use efficiency (WUE) of maize and sorghum stands in years 2010–2012. WUE values were calculated from the daily values of actual evapotranspiration (ET_a, kg/m^2) and daily biomass growth (B_{calc}, g/m^2) for days when the daily sum of R_g was ≥ 18 MJ/m^2. DOY – day of the year

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kg. In 2012, the highest daily WUE was 11.81 g/kg for maize and 11.51 g/kg for sorghum.

Pan et al. (2011) reported higher sorghum evapotranspiration in humid years than in maize crop, while lower in normal or dry years. However, the evaluation of water use efficiency between these crops is complicated because of the late sorghum sowing date, which leads to the shift of developmental stages. In the experimental environment, the generative sorghum stages are usually not reached because the subsequent development of the stands is limited by low temperatures at the end of the growth period.

In conclusion, the three-year experiment in this study demonstrated higher maize actual evapotranspiration in the years with higher sum of precipitation (2010 and 2011) whereas higher sorghum evapotranspiration was observed in the dry year 2012. It suggests the improved sorghum resistance to water stress. However, this sorghum ability did not result in higher production of the above-ground biomass.

Higher production of maize above-ground biomass was measured consistently over a three-year period, together with reduced soil VWC in comparison with sorghum. Maize and sorghum provided similar sap flow values with high variability among individual plants.

Transpiration values suggest lower levels of evaporation per unit area in sorghum stands, probably due to higher LAI values. The sorghum provided similar or higher WUE values than maize during the period of intensive prolongation growth. However, this higher water use efficiency did not contribute to higher biomass production in these experimental conditions. At the end of this period, WUE values were comparable or lower contrast to maize. The WUE decrease might be associated with reduced formation of generative organs of sorghum. This formation should increase the total aboveground biomass production and probably should lead to WUE enhancement in comparison with maize.

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