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Leaf area index for common reed (*Phragmites australis*) with different water supplies in the Kis-Balaton wetland, Hungary, during two consecutive seasons (2014 and 2015)

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Abstract— Seasonal progression of common reed (*Phragmites australis*) growth has been described by leaf area index (*LAI*), a key variable of crop growth, during two consecutive seasons at the Kis-Balaton wetland (*KBW*) in Hungary. The key objective of this study was to quantify the morphometric variability of *LAI* among common reed beds while distinguishing between established plant canopies with standing water (*SR*) and without water cover (*DR*). Seasonal mean *LAI* of plants with unlimited access to water was 3.21 ± 0.36 and 2.66 ± 0.34 for 2014 and 2015, respectively, while that of plants growing without water cover was 1.11 ± 0.22 and 0.89 ± 0.19. Common reed may be more sensitive to the presence or lack of continuous water cover than to variable weather conditions. Weekly *LAI* curves with two different water supplies as a function of growing degree day *(GDD)* were conducted to estimate the timing of peak *LAI.* Modeling the sums of seasonal evapotranspiration (*ET*) of swamp reed in *SR* showed only slight increases (56.3 mm and 50.8 mm) in 2014 and 2015, respectively. Total *ET* showed significant variation between both seasons, with the 2015 sum of *ET* being almost twice that of 2014. The findings of this study improve our knowledge about the growth of common reed *LAI* under variable weather conditions and water cover. The response of a plant, including *LAI*, to varying environments, may illuminate a course of action in wetland conservation programs. In addition, estimates of *LAI* based on meteorological variables might serve as useful inputs for different *ET* and growth models.

Key-words: common reed, weather impacts, growing degree day, lead area index

1. Introduction

Common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) is a cosmopolitan perennial vascular plant that occupies a wide range of climatic habitats, and is known as the most common wetland plant (*Lambertini et al.*, 2008). In the Northern hemisphere, common reed occurs at latitudes between 70° N and the tropics (*Clevering* and *Lissner*, 1999). Differences in the length of common reed's growing seasons witnessed at different latitudes may be a relatively simple evolutionary adjustment based on temperature (*Clevering et al.*, 2001). Among other stressors such as salinity, nutrient supply, cold or other severe or extreme weather conditions, one of the main ecological stressors in common reed stands that affects its growth capacity is water level (*Bresciani et al.*, 2011, *Engloner*, 2009).

Leaf area index (*LAI*), a key-variable for plant growth, is defined as half the total green leaf surface area per unit ground surface, and is a useful measure of seasonal canopy dynamics (*Savoy* and *Macay*, 2015). Leaf properties should be used as indicators of vegetation activity of the biosphere-atmosphere continuum (*Burba* and *Verma*, 2001). The period of activity of macrohyte vegetation can be typified by the seasonal pattern of green leaf area (*Burba et al.*, 1999). The *LAI* approach that allows plant growth to be monitored also has limitations associated with the time interval (10-14 days or longer) between plant sample collections (*Brenner* and *Ham*, 1999).

Size of the foliage area not only affects plant productivity but almost all characteristics related to the extent of evapotranspiration (*ET*) (*Burba* and *Verma*, 2001). Wetland-to-wetland differences in leaf area cause large variations in canopy *ET*, because one determinant of *ET* is biological control by manipulating the size of foliage (i.e., transpiration) area (*Pedescoll et al.*, 2013).

A concept used worldwide, growing degree days (*GDD*), is based upon the assumption that below a minimum (base) temperature (T_o), plant physiological processes are suspended (*McMaster* and *Wilhelm*, 1997). *Irmak et al.* (2013) suggested 7 °C for common reed T_o when calculating *GDD* for Nebraska, USA.

Zonation of emergent plants is the result of their adaptation to complete flooding and extended dry periods (*Sorrell et al.*, 2000). The phenotypic plasticity of common reed allows it to modify its morphological response by changing the photosynthetic area (*Clevering* and *Lissner*, 1999) hence its importance and link to *LAI*.

Morphological analyses of common reed canopies growing at different water depths frequently provide contradictory results (*Engloner*, 2009) most likely due to differences in observation sites and methods applied. Our area of investigation, the Carpathian Basin, is expected to have drought and floods creating extreme weather conditions with variable inter- and intra-annual temperature and precipitation events. Changeable weather makes the study site worthy of an *LAI* investigation, where summers may display either arid or humid conditions.

There is extremely scant literature that has examined the impact of water cover on common reed leaf expansion. Measurements related to a wetland's *LAI* are still uncommon, because they involve complex and time-consuming processes. To fill this gap, the primary goal of this study was to estimate *LAI* values by using easily accessible meteorological elements. Over a two-year period, two different water covers were studied, equivalent to two seasons in each year. Different models are in use to estimate wetland *ET*, where the most important input related to plant growth is *LAI* (WETSIM: *Poiani* and *Johnson*, 1993; TSEB: *Kustas* and *Norman*, 1999). The second objective of the present investigation was to parametrize *LAI* seasonal variation as an input of these models. Ultimately, we wanted to feature a distinct common reed-specific distribution curve throughout the growing season that was closely related to plant development. Poor analysis of the seasonal change in *LAI* may cause serious inaccuracies in estimating vegetation productivity and transpiration due to the close link between leaf size and carbon fluxes (*Ryu et al.*, 2008). Our results are important for further understanding of wetlands' characteristics, and for protecting their ecological function worldwide.

2. Materials and methods

2.1. Study site

Lake Balaton (surface area: 596 km^2, average depth: 3.25 m, water volume: 1.98 km^3) is a vulnerable shallow freshwater lake in Hungary, closely connected to the Kis-Balaton wetland (KBW), which serves as a filter for the lake. Artificial water reservoirs were also constructed, establishing the Kis-Balaton Water Protection System (KBWPS). As part of a two-step project, Hídvégi Pond (52 km^2, water retention time 30 days) and a part of Fenéki Pond (FP) (16 km^2, water retention period 90 days) started to function in 1985 and 1992, respectively (*Tátrai et al.*, 2000).

The sample site, FP [geographical position: 46°39′N; 17°12′E; mean elevation 104.5 m (max.: 106 m, min.: 103 m) above Baltic Sea level] is located on the south-west side of Lake Balaton (*Fig. 1*), 7.75 km far from the Meteorological Research Station of Keszthely. An average water depth of 0.4–0.6 m is maintained at about one-third of the study area (16 km^2). The remaining part of FP has no constant water cover and only residual water puddles may appear temporarily. The estimated area covered by residual water is less than 1%.

The characteristic soil is organic (peat), formed by excess moisture from groundwater and precipitation, and the shoreline is anchored, allowing it to dissipate erosive forces (*Istvanovics*, 1994).

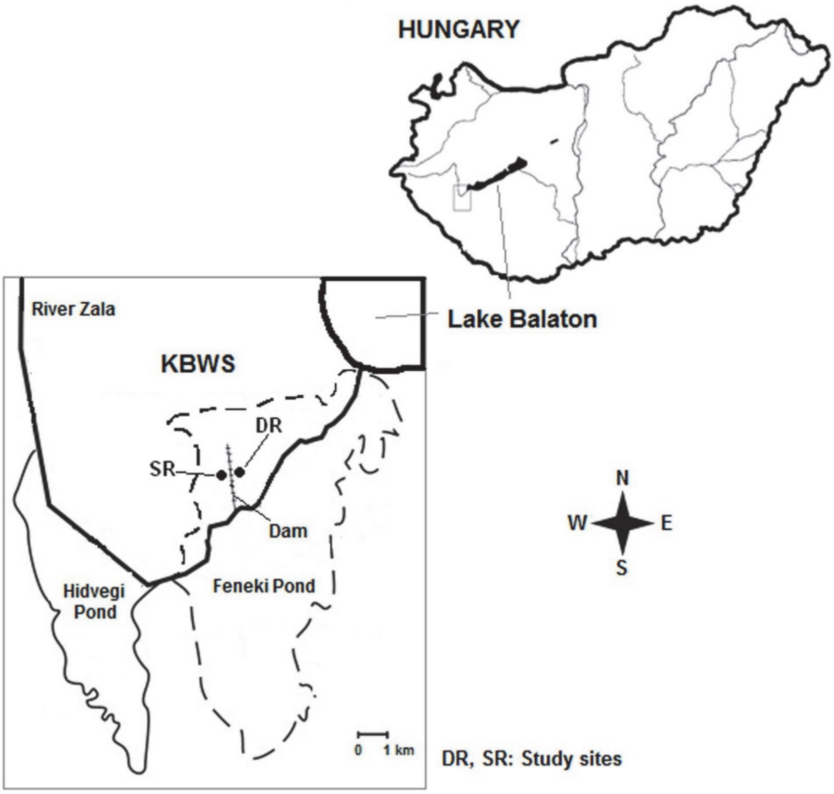

Fig. 1. Map of the Kis-Balaton wetland (KBWS: framed leftward graph) of Hungary, showing the location of Fenéki Pond, FP (study area – bordered by a continuous line) with sampling sites for dryland (DR) and water-covered (SR) common reed stands along the embankment (dam). Hídvégi Pond is highlighted by a dotted line. River Zala is the largest inflow of watershed, and is denoted by a thick line.

2.2. Macrophytes of sample site

Based on on-site macrophyte composition and cover observations (*Anda et al.*, 2014), the dominant emergent macrophytes at FP were common reed, cattail (*Typha angustifolia*, *Typha latifolia*), and sedge (*Carex acutiformis*, *Carex elata*, *Carex riparia*) accounting for about 70% of the canopy cover. The average ratio of the open water surface was only 6% in the long-term (about 30 years). Other minor plant categories, such as shrubs (*Salix cinerea*, *Salix alba*), tree patches (*Salix fragilis*, *Alnus glutinosa*, *Populus tremula*), or grassland (dominant species: *Festuca rupicola*, *Arrhenatherum elatior*, *Alopecurus pratensis*) were also identified with much less than 10% cover (*Anda et al.*, 2014). Common reed was used as the sample plant in our study as it accounted for more than 50% of the macrophyte vegetation cover of FP.

2.3. Weather with meteorological and related ET observations

Meteorological observations were carried out on the northern edge of KBW, at the Meteorological Research Station of Keszthely (latitude: 46°44′, longitude:

17°14′, elevation: 124 m above Baltic Sea level) with a QLC-50 (Vaisala, Helsinki, Finland) automatic climatic station equipped with a CM-3 pyranometer sensor (Kipp & Zonen Corp., Delft, the Netherlands). The combined sensors for air temperature (T_a) and relative humidity (RH) measurements were placed at 2 m above the soil surface. Signals from meteorological sensors were collected every 2 s, and 10-min means were logged by the climatic station.

The climate of the study site is temperate continental with an annual mean long-term (1871–2014) T_a of 10.5 °C showing a monthly minimum of –1.1 °C in January and reaching a maximum of 21.1 °C in July. The annual mean precipitation (P) is 673.3±137.9 mm with fairly large monthly variation. The monthly mean P varies between 32.7 mm and 76.1 mm in the driest January and wettest July, respectively. The rainfall distribution at KBW shows a special character and is concentrated between May and July, contributing to over half of the yearly sum. Yearly precipitation is highly variable due to characteristics of the Carpathian Basin.

The 2014 and 2015 seasons were warm with a T_a of 0.5 ($P(T<=t)=0.349$) and 0.9°C ($P(T<=t)=0.048$) higher than its long-term mean (*Table 1*).

Table 1. Mean monthly air temperatures (T_a) and monthly precipitation sums (P) for the study seasons. Data were calculated for the time period 1971–2000

	Apr	May	Jun	Jul	Aug	Sep	Oct
T_a [°C] 1971–2000	10.5	15.7	18.7	20.5	20.1	15.7	10.3
P [mm] 1971–2000	50.5	59.6	78.5	73.5	65.1	57.1	49.0
T_a [°C] 2014	12.3	14.7	18.9	21.2	19.1	16.1	12.7
P [mm] 2014	58.6	76.5	59.7	113.1	148.1	159.7	68.3
T_a [°C] 2015	10.8	15.6	19.5	22.9	22.6	16.6	9.7
P [mm] 2015	4.0	102.3	20.9	60.9	70.3	62.9	151.6

Climatic norms of 1971–2000 were applied for comparison, and the P of both experimental seasons was contrasted. In the wetter year, 2014, the rainfall sum during the vegetation season was 44.8% ($P(T<=t=0.035$) higher than the long-term average. By contrast, the growing season was dry in 2015, with 8.7% ($P(T<=t)=0.794$) less than long-term mean sum of rainfall. However, the summer of 2015 was even drier, and the lack of rain water until September 1 was 17.9% lower than the climatic norm. The 156 mm monthly precipitation in October raised the seasonal mean precipitation of 2015, which might be considered to be less decisive for common reed development. Interannual variation in monthly mean T_a was large in July, +1.0 and +1.7 °C higher than the long-term average in 2014 and 2015, respectively, corresponding to the most sensitive period of common reed growth patterns. In September 2014, serious flooding events occurred which increased the surface water level in part of the studied area (*Fig. 2*). The FP water level rose from 0.6–0.7 m in April to 1–1.5 m in September. At the same time, the area of our second (dry) sample site remained dry, without any surface water cover.

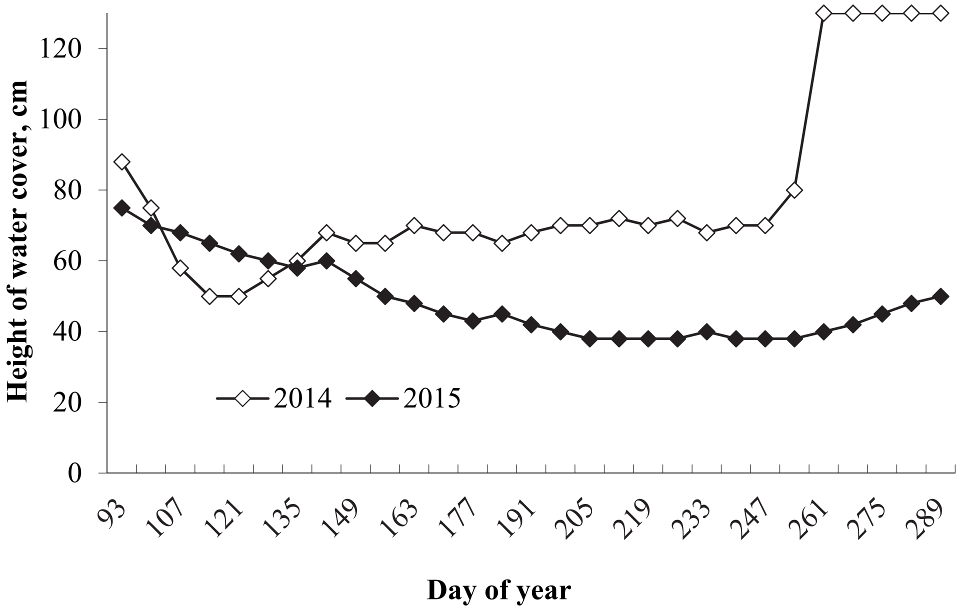

Fig. 2. Seasonal trend of standing water level measured on-site of SR relative to surface (0 cm) during the two seasons. In DR there was no standing water in both summers.

On the basis of six years of on-site observations, the ET of the reed bed was modeled using an earlier tested empirical approach for warm seasons (*Anda et al.*, 2014):

$$ET = 0.142R_n + 0.211T_a - 0.042RH + 0.134LAI + 1.082, \tag{1}$$

where R_n is the net radiation.

This model works on a daily basis. In this study, weekly ET sums were presented for two water levels, i.e., common reed standing in water (SR) and plants without water cover (DR).

2.4. Plant observations

In the present study, we distinguished *a priori* two different stand morphotypes (treatments) of common reed as the dominant macrophyte of FP:

– Plants standing in water, where evaporation from the water body would be limited only by available energy under the given surface and atmospheric conditions. These plants were grown in swampland areas (swamp-reed, or SR).

– Plants of dryland conditions (dry-reed, or DR), located at the foot of land sloping down to FP, where the latent heat, including evaporation, would be limited due to shortcomings in soil moisture.

Measurements of weekly *LAI* (dimensionless: size of green leaf area [m^2] above unit ground surface [m^2]) were used to estimate vegetation growth. After the plants emerged, leaf area was measured on 10 randomly chosen sample shoots every week using a portable automatic planimeter (LI-3000A, LI-COR Inc., Lincoln, NE, USA). Shoots that were selected were characteristic of the whole canopy plant stand within each water treatment. After manually counting shoot density from five subplots with an area of 0.25 m^2 within the wetland for each treatment, *LAI* was expressed every week. *LAI* measurements started when it was approximately 0.1–0.3 (day of year, *DOY* ~100), similar to earlier studies on common reed growth patterns (*Irmak et al.*, 2013, *Burba et al.*, 1999).

The *LAI* values were regressed against daily cumulative *GDD*. When calculating *GDD* for common reed, we used 7 °C as the base temperature T_o, because the on-site observed temperature for common reed emergence coincided with 7 °C in the first half of April:

$$GDD = \sum(T_a - T_0), \tag{2}$$

in which both temperatures, T_a and T_0, were considered on a daily basis.

2.5. Statistics

To compare the impacts of two water levels, a two-tailed *t*-test was used. Two-way analysis of variance (ANOVA/*t*-test) was performed to examine the impact of seasons and water cover on *LAI*. Differences were considered to be significant at $\alpha = 0.05$.

Multiple stepwise regression analysis was used to assess the influence of meteorological variables on *LAI*. To compare measured and simulated (based on meteorological variables) *LAI*, a linear regression ($y = a + bx$) was used (measured *LAI* data as dependent variable *y*, simulated *LAI* as independent variable *x*). The accuracy of the estimate was considered to be acceptable when the slope forced through the origin of the regression (1:1 line) was not significantly different from 1. All tests were carried out with SPSS Statistics version 17.0 software (IBM Corp., New York, USA).

3. Results

3.1. Impact of meteorological elements on LAI

Among the weekly-based meteorological variables, T_a, *RH*, and *P* were included in the analysis (*Table 2*). In both seasons, T_a influenced *LAI* the most ($r = 0.78 - 0.9$), irrespective of water supply. In 2014, only a mild correlation was found between *LAI* and *P* ($r = 0.45 - 0.46$). In 2015, the *r* values for *P* were 0.00 – 0.01 in both water supplies, when water shortage (summer drought) occurred. Irrespective of the season, a weak negative correlation was demonstrated for *RH* in both water levels ranging from $r = 0.00$ to –0.14. A high positive correlation was observed between the *LAI*s of the two water supplies ($r = 0.99 - 0.99$ for both water supplies). The probability levels are presented in *Table 2*.

Table 2. Correlation coefficients (r) for weekly mean leaf area index, *LAI* in dryland region (DR) and common reed stand with water cover (SR) during a two-season (2014–2015) study. T_a: weekly mean air temperature; *RH*: weekly mean relative humidity; *P*: weekly precipitation sum. Number of observations was 27 in 2014 and 32 in 2015 for each correlation

Season	T_a [°C]	*RH* [%]	*P* [mm]
DR-2014	0.783^{***}	–0.036	0.448^{*}
SR-2014	0.778^{***}	–0.060	0.456^{*}
DR-2015	0.9^{***}	–0.009	–0.004
SR-2015	0.904^{***}	0.005	0.011

* Marginally significant correlation |r|>0.1, p<0.01

** Marginally significant correlation |r||>0.1, p<0.001

*** Significant correlation |r||>0.4, p<0.0001

3.2. Growth curve for LAI

There was a gradual increase in weekly *LAI* until peak *LAI* and then a decline throughout both growing seasons associated with plant biological characteristics and meteorological conditions (*Fig. 3*). Irrespective of the year and water supply, leaves started to expand in April (*DOY*: 90–93), and exhibited an increasing trend with longer periods of solar radiation until the end of July (*DOY*: 200–205) corresponding to the most intense growth of common reed (*Fig. 3*). Thereafter, *LAI* decreased parallel to the decline in radiation throughout the remainder of the growing season (*DOY*: 290–294). The length of the growing season was about one week longer in 2014 than in 2015 (data not shown).

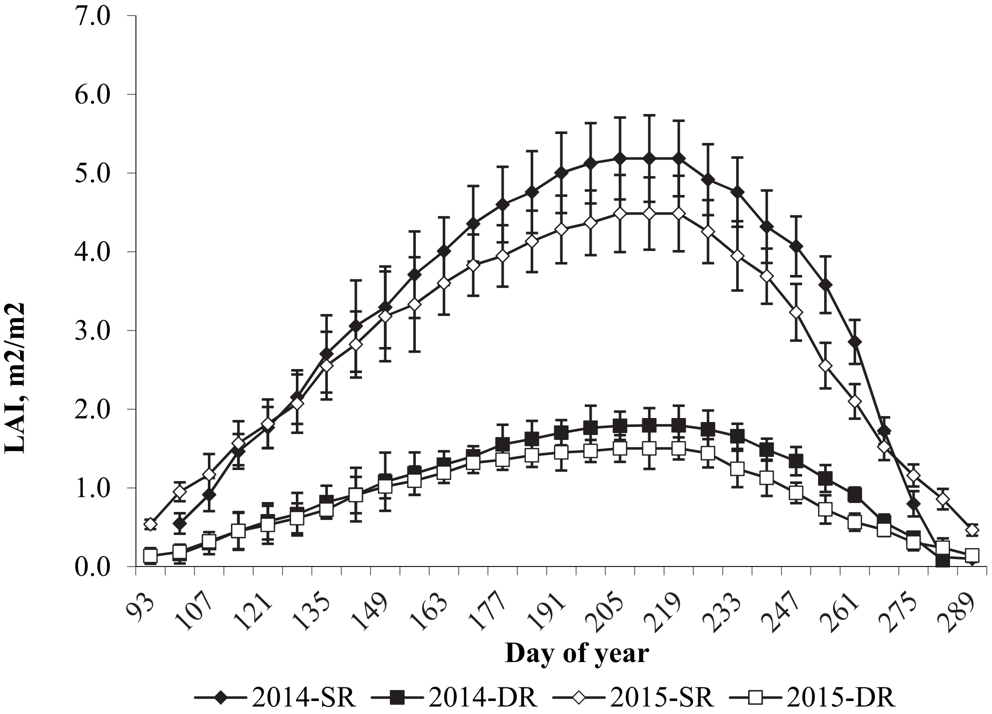

Fig. 3. Seasonal pattern of weekly mean leaf area index, *LAI,* in two growing seasons (2014 and 2015). DR and SR represent common reed without water cover and crops standing in water, respectively.

Weekly mean *LAI* in 2014 ranged from 0.1 to 0.3 at the beginning and at the end of the growing season, reaching 1.79 and 5.19 in DR and SR, respectively (*Fig. 3*). However, the initial and final *LAI* values remained similar for 2015, and the peak values were 1.50 for DR and 4.49 for SR. At both sites, maximum *LAI* peaked in the last 10 days of July, irrespective of seasonal weather. Seasonal means of common reed *LAI* with unlimited access to water were 3.21 ± 0.36 and 2.66 ± 0.34 for 2014 and 2015, respectively. The *LAI* of plants in DR were 1.11 ± 0.22 and 0.89 ± 0.19 for the same time period. Maximum average *LAI* of SR was 4.84 for the two growing seasons and was higher than the mean *LAI* of both seasons for DR, namely 1.64.

The response of common reed *LAI* to changing water level in the two seasons was similar: water shortage significantly decreased seasonal mean *LAI* by 99.7% (*P(T<=t)* = 0.0001) and 97.2% (*P(T<=t* = 0.0001) in 2014 and 2015, respectively. In the wet 2014 season, seasonal mean *LAI* was 21.1% (*P(T<=t)* = 0.140) and 18.7% (*P(T<=t)* = 0.032) higher in DR and SR, respectively, than in the dry 2015 season.

There are two basic factors that affect *LAI*, the size of the green leaf area per shoot and the shoot density. The impact of weather on seasonal mean leaf area per shoot was less pronounced, as only a 2.3% (*P(T<=t)* = 0.366) and 6.5%

(*P(T<=t* = 0.003) increment in favor of wet 2014 was observed for SR and DR, respectively. In contrast, the effect of water cover was at least two-fold higher and the average leaf area per shoot in SR and DR was 12.2% (*P(T<=t)* = 0.0001) and 16.4% (*P(T<=t)* = 0.0001) higher in 2014 and 2015, respectively. Based on a two-season average, the mean shoot density for DR and SR stands was 22 ± 8.21 and 58 ± 21.64 shoot m^{-2}. No significant differences in shoot density between both seasons were observed [DR: (*P(T<=t)* = 0.735); SR: (*P(T<=t* = 0.697)]. The lack of water cover resulted in a 90.5% (*P(T<=t* = 0.012) and 90.9% (*P(T<=t)* = 0.020) decrease in average shoot density in the 2014 and 2015 growing seasons, respectively.

The maximum number of leaves on culms was 11.6 ± 3.0, 13.6 ± 2.33, 12 ± 2.45 and 14.4 ± 3.44 in DR (2014), SR (2014), DR (2015) and SR (2015), respectively, during flowering. The number of leaves per shoot was not strongly linked to season or water supply. This latter parameter tended to increase in approximately two leaf layers (*P(T<=t)* = 0.129 and *P(T<=t)* = 0.061 in 2014 and 2015, respectively) in SR stands. The change in the number of leaves between the seasons was also not significant (SR: *P(T<=t)* = 0.541; DR: *P(T<=t)* = 0.648).

Changes in seasonal *LAI* trends were plotted as a function of *GDD* (*Fig. 4*). Although the best fit was a three-degree polynomial in all treatments, the trend of the curves was impacted by different water supply levels, irrespective of the season (*Fig. 5*).

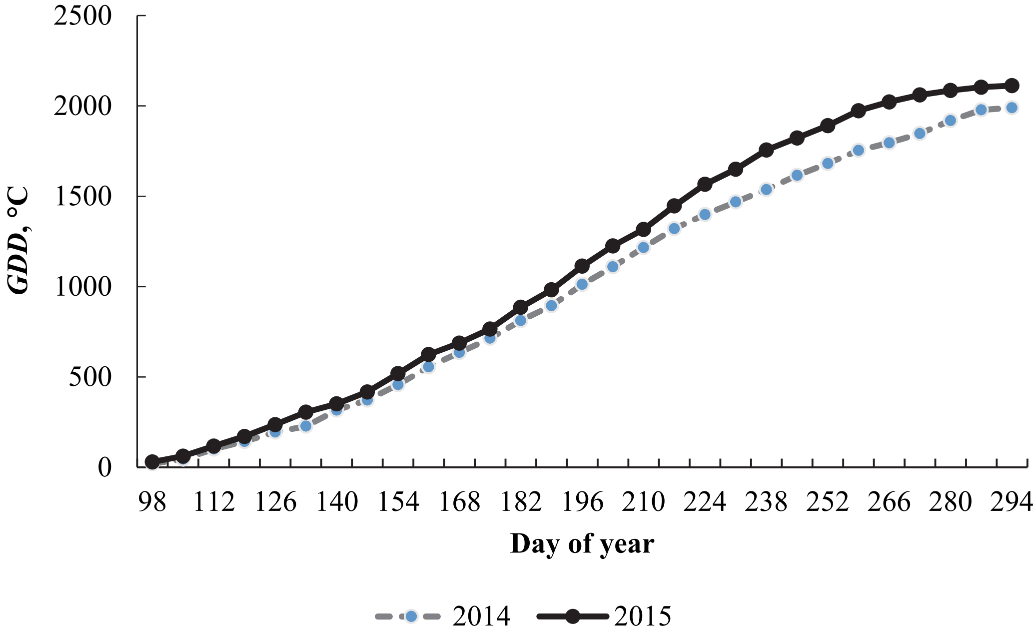

Fig. 4. Cumulative growing degree day, *GDD* (base temperature of 7°C) for common reed at the Kis-Balaton wetland, Hungary during the 2014 and 2015 growing seasons.

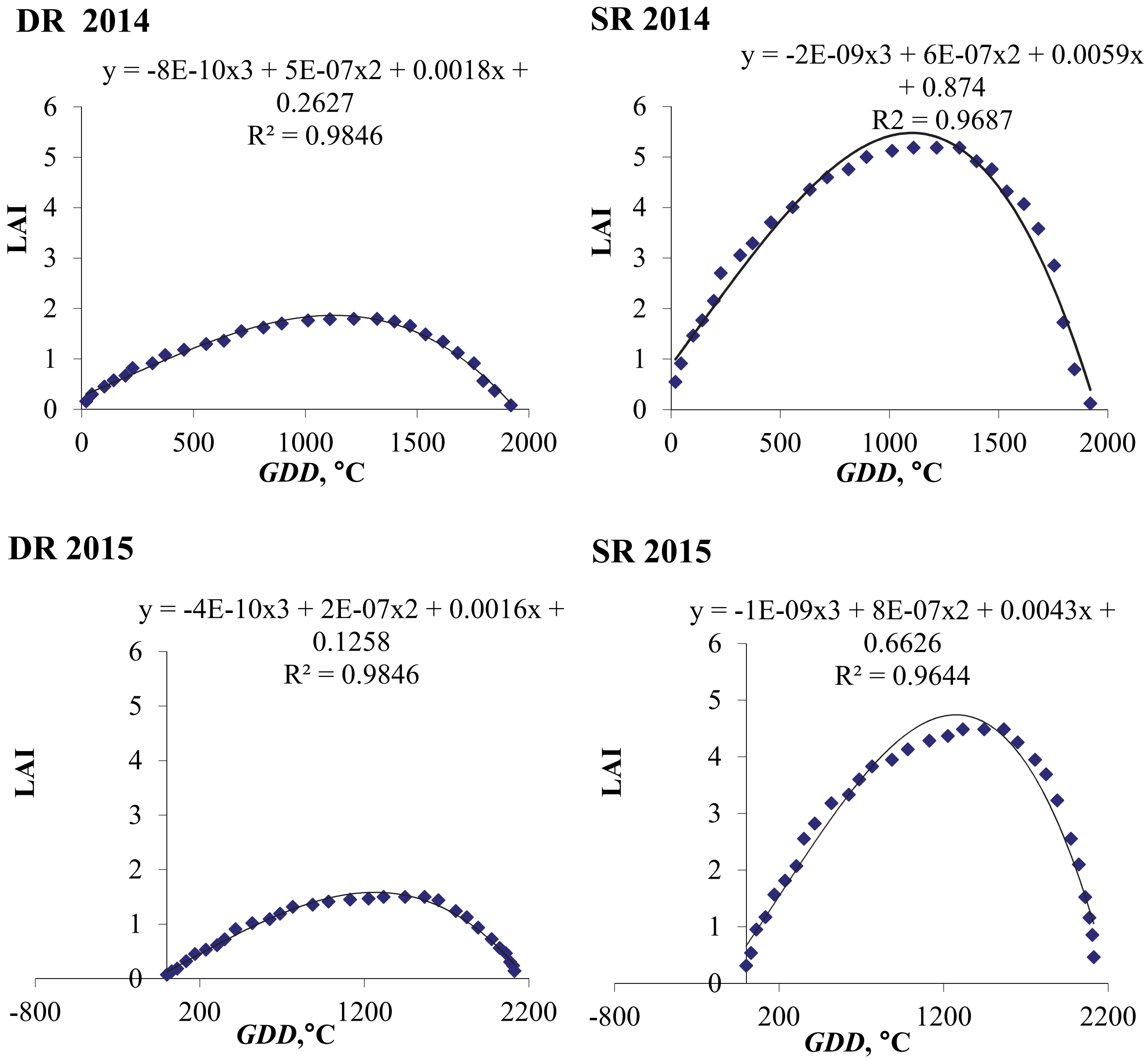

Fig. 5. Seasonal variation in weekly mean *LAI* for common reed as a function of growing degree days, *GDD* in 2014 and 2015. DR and SR represent common reed without water cover and crops standing in water, respectively.

In 2014, the cumulative *GDD* value was 1990 °C, whereas it was 2112 °C at the end of October in 2015 (*Fig. 4*). *GDD* curves were concurrent until the end of July. *LAI* curves for common reed in SR and DR zones were developed as a function of *GDD* (*Fig. 5*). Although the slopes and intercepts of the treatments that were studied differed, every curve followed a lowest applicable third-degree polynomial function with high R^2 and similar data scatter. The time at which peak *LAI* appeared (*DOY*: 200–210) was close to other *DOY* values in each water level. During peak *LAI*, a 300–400 °C higher *GDD* was measured in the warmer 2015 than in the 2014 season.

3.3. Estimation of common reed evaporation based on LAI measurements

The daily *ET* rates presented an obvious seasonal pattern. In 2014, daily mean *ET* rates averaged 4.2 and 4.5 mm day^{-1}, with a range of 0.2 to 8.1 and 0.4 to 8.5 mm day^{-1} for DR and SR, respectively. A moderate increase was observed in 2015 when daily *ET* rate means were 4.8 and 5.1 mm day^{-1}, with a range of 0.2–8.7 and 0.4–9.1 mm day^{-1}, for DR and SR, respectively.

Based on weekly *LAI* measurements, seasonal variations in weekly *ET* totals were plotted (*Fig. 6*). In both growing seasons, weekly *ET* sums followed the pattern of *LAI* and solar radiation. *ET* sums increased from about 13–15 mm week^{-1} in April to a peak magnitude of about 50 – 60 mm week^{-1} during July, and then decreased to below 16 –18 mm week^{-1} during October.

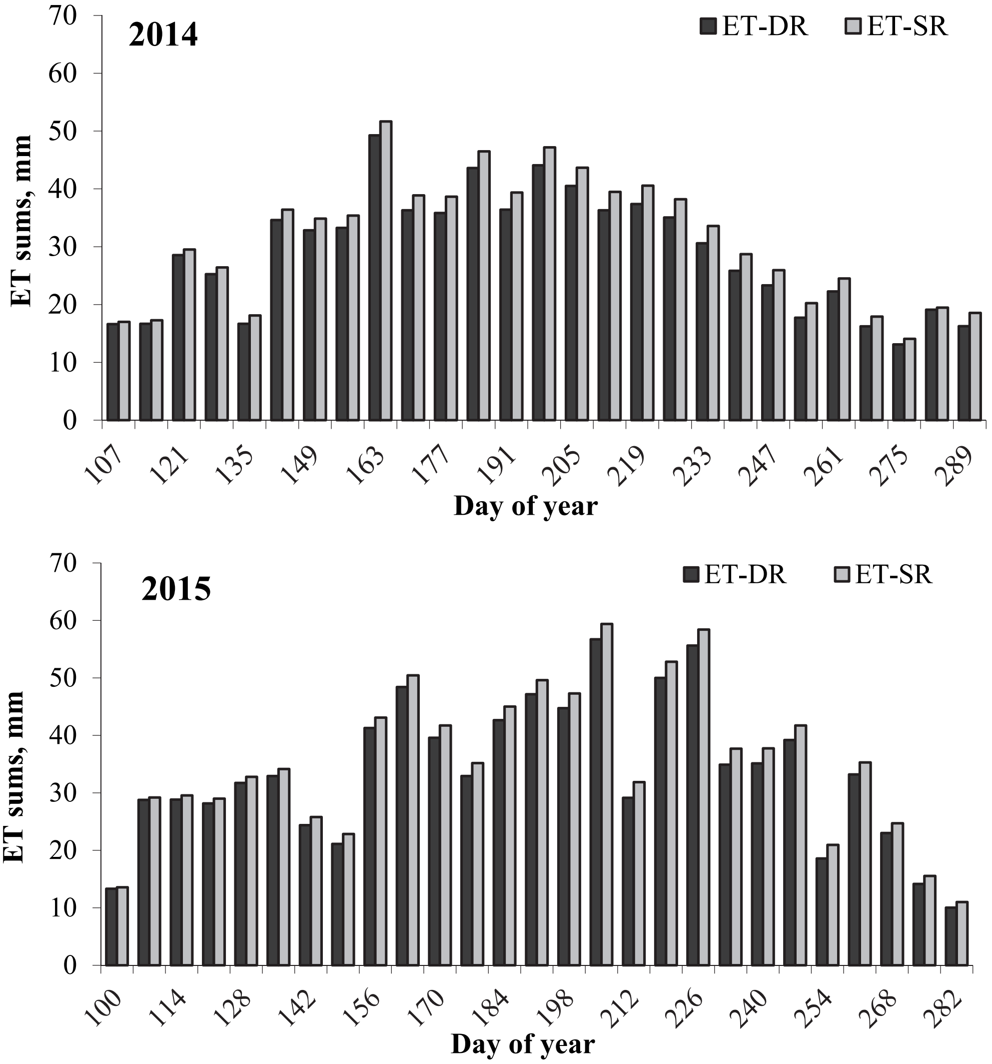

Fig. 6. Model results of weekly evapotranspiration (*ET*) sums for the 2014 and 2015 seasons. ET-DR and ET-SR represent common reed *ET* without water cover and crops standing in water, respectively.

Deviations of daily *ET* rates between seasons and water supply levels were highly significant. In the warm 2015 season, daily mean *ET* rates were larger than the *ET* rates of the previous wet season of 2014, with 13.3% ($P(T<=t)=0.0001$) in DR and 12.5% $P(T<=t)=0.0001$) in SR. The impact of changing water level was less noticeable and only 6.9% ($P(T<=t)=0.004$) and 5.5% ($P(T<=t)=0.0001$) increases were modelled for 2014 and 2015, respectively.

4. Discussion

4.1. Impact of weather

In this study, *LAI* was strongly correlated with weekly mean T_a, independently of the presence of standing water: 0.9 °C higher seasonal mean T_a in 2015 caused 18.7% and 21% lower mean *LAI* in SR and DR, respectively. Similar to our investigation, an increase in T_a of 1.5 °C reduced the *LAI* of common reed by 27% when averaged across the growing season at Yangtze Estuary, China (31°38′ N, 121° 58 ′ E) (*Zhong et al.*, 2014).

Univariate ANOVA showed a significant effect of season ($P(T<=t)=0.008$) and water level ($P(T<=t =0.0001$) on *LAI*, but there was no interaction between both variables, i.e., season × water ($P(T<=t)=0.193$) (*Table 3*).

Table 3. Univariate analysis of variance for weekly mean leaf area index, *LAI,* compared to all treatments (2014 and 2015 seasons; two water supplies)

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	19.821[a]	3	6.607	81.444	.000
Intercept	77.028	1	77.028	949.499	.000
Season	.757	1	.757	9.326	.008
Water level	18.915	1	18.915	233.160	.000
Season × water level	.150	1	.150	1.845	.193
Error	1.298	16	.081		
Total	98.148	20			
Corrected Total	21.119	19			

[a] $R^2 = 0.939$ (Adjusted $R^2 = 0.927$)

The quality of the influence, i.e., the correlation coefficient for *P*, was negligible not only in plant stands with no limited access to water (SR), but in the DR canopy as well. In 2014, multiple stepwise regression, in some cases, including three candidate explanatory meteorological elements (T_a, *RH*, and *P*) in both SR and DR, produced more accurate results than a single correlation, because *LAI* responded to other meteorological factors as well. The adjusted coefficient of determination (r^2) produced by SPSS was used to check the model. In 2014, the best projections were those equations containing all meteorological elements (*Table 4*). In the next season, probably due to a dry summer, *P* and *RH* were excluded from the estimate. Stepwise regression analysis indicated that irrespectively of season and water supply, T_a was the driving force for *LAI* growth at the study site.

Table 4. Multiple stepwise regression models to predict leaf area index (*LAI*) from meteorological variables (T_a: weekly mean air temperature; *RH*: weekly mean relative humidity; *P*: weekly precipitation sum). Model fit was controlled by adjusted r^2

	Adjusted R^2	**F**	**F sig.**	**SE of coefficient**	**Regression equation**
DR-2014/1	0.597	39.567	0.000	Const.=0.337 T_a=0.019	$LAI_{DR}=0.121T_a–0.964$
DR-2014/2	0.756	41.268	0.000	T_a=0.759 P=0.403	$LAI_{DR}=0.118T_a–0.011P–1.145$
DR-2014/3	0.790	33.669	0.000	T_a=0.717 P=0.546 RH=–0.247	$LAI_{DR}=0.111T_a+0.015P+0.021RH+0.521$
SR-2014/1	0.589	38.26	0.000	Const.=0.988 T_a=0.056	$LAI_{SR}=0.349T_a–2.645$
SR-2014/2	0.755	41.141	0.000	Const.=0.773 T_a=0.044 P=0.008	$LAI_{SR}=0.338T_a+0.033P–3.180$
SR-2014/3	0.808	37.458	0.000	Const.=2.189 T_a=0.039 P=0.008 RH=0.027	$LAI_{SR}=0.316T_a+0.46P–0.073RH+2.539$
DR-2015	0.805	128.593	0.000	Const.=0.127 T_a=0.007	$LAI_{DR}=0.083T_a–0.546$
SR-2015	0.811	134.390	0.000	Const.=0.355 T_a=0.020	$LAI_{SR}=0.237T_a–1.325$

4.2. Common reed growth

In 2015, growth initiation was delayed by about one week compared to 2014, due to lower spring temperatures. This may be one reason why the mean peak *LAI* was also lower. *Soetaert et al.* (2004) found a pronounced effect of postponing growth initiation (i.e., late timing of bud burst in spring) on common reed growth characteristics, including *LAI*.

The peak *LAI* was calculated from the inflection points of *Fig. 5* as the second derivative of the third-degree polynomial. Good agreement was found in calculated and measured *LAI* peaks (*Fig. 7*).

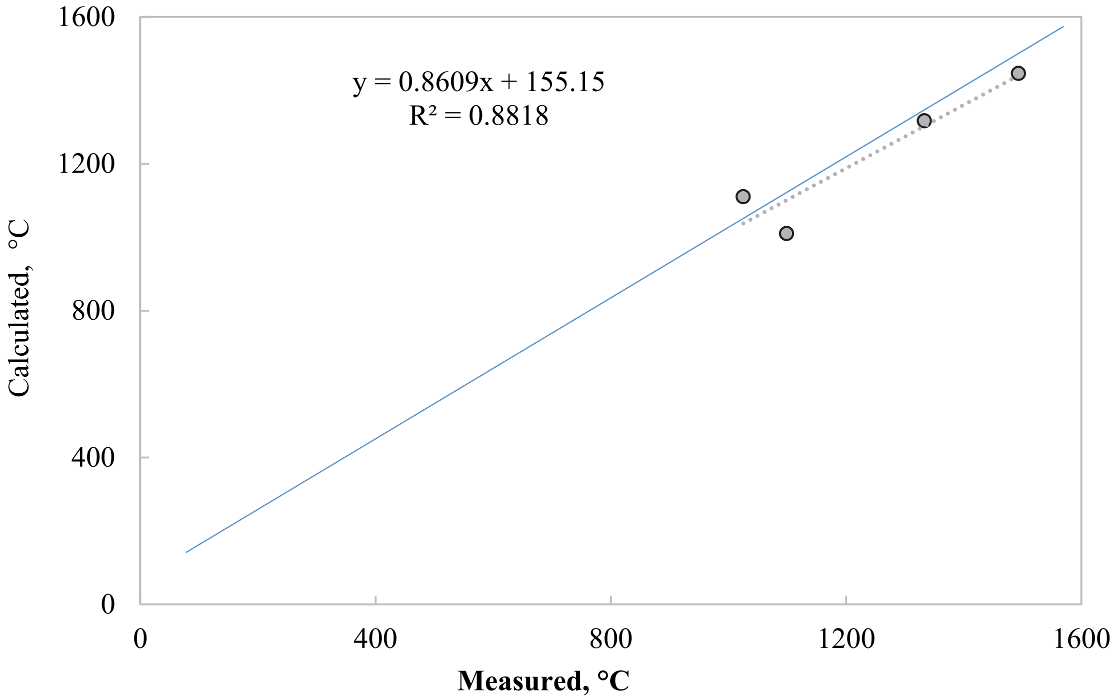

Fig. 7. Comparison of measured (*Fig. 3*) and calculated peak *LAI* using GDD concept during the 2014 and 2015 study period. The four calculated peak *LAI* are the inflection points determined from the 2nd derivative of the third-degree polynomials of *Fig. 5*.

Peak *LAI* was followed by plant senescence, and *LAI* values continued to decline slightly until the end of October (*GDD*~2000 °C). Based on slopes of fitted least squared linear regression lines, there was significant variation in the descending branch (leaf withering) of weekly *LAI* curves (*Table 5*). Different slopes were found in the two growing seasons for each of the two water supplies. On the basis of these slopes, the steepest curve was observed in SR during 2014. Flooding during the fall of 2014 might have been the responsible driver of intense *LAI* decline in the SR canopy. In 2015, a more intense slope was also observed for SR than for DR.

Table 5. Linear regression equations (with slopes) of curves fitted to descendent branches of leaf area index, *LAI* vs. growing degree day, GDD (2014–2015). Abbreviations DR and SR are as in *Table 2*

Treatment	**Regression equation**	r^2
DR-2014	–0.0033x + 2.1632	0.96
SR-2014	–0.014x + 5.4377	0.97
DR-2015	–0.003x + 1.6331	0.97
SR-2015	–0.010x + 4.5386	0.97

Irrespectively of the season, the *LAI-GDD* curves were not identical on both sides of the graph, i.e., asymmetry was displayed, and the slopes of descending branches (leaf withering) were steeper than the ascending slopes (*Fig. 5*). The largest deviation in 2014 was associated with adverse meteorological conditions, mainly in the SR canopy. This part of the wetland was submerged in fall, and heavy storms and rough waves might have sped up leaf degradation. In all other periods, the water level of SR was at a constant height. In contrast, in the same time period, there was no water cover in DR. Two different water supplies in this study reflected differences in common reed *LAI* in wetland habitats due to changing water levels. *Windham* (1999) reported that, within a marsh, there are variations in the rate of expansion of common reed that are related to micro-site variations in water level.

Bresciani et al. (2011) found that water level is a driving factor for changes in *LAI* by forcing an abundance of stems in common reed at the lakeshore of Lake Garda, Italy. *Russell* and *Kraaij* (2008) found that common reed in wet zones formed more shoots (i.e., greater shoot density) than in drier zones in a South African estuarine lake system. In our study, the enhanced *LAI* of SR in both seasons is attributed to the constant (~0.5 m) water cover that induced higher shoot density. Irrespectively of the season, about 90% ($P(T<=t) = 0.012$–0.02) more shoots were counted in the SR stand (data not shown), similar to the observations of *Russell* and *Kraaij* (2008) in South Africa and *Coops et al.*, (2004) in the Netherlands for common reed stands with a 30–80 cm water depth. However, there are also some studies that show higher shoot density for common reed in dryland conditions (*Engloner*, 2004; *Bodensteiner* and *Gabriel*, 2003). *Coops et al.* (2004) investigated common reed expansion with fluctuating water levels at freshwater Lake Volkerak-Zoommeer in the Netherlands. The authors found that the best height of aboveground water level ranged between 25 and 40 cm, close to our standing water level. In our study, height of the water cover increased by 1–1.5 m only temporarily due to flooding in September 2014, which enhanced leaf withering (*Fig. 3*). Results of our study are comparable with those of *Hudon et al.* (2005) for Quebec, Canada, in which common reed retreated when the water level in summer was higher than 50 cm.

A significant decline of 18.7% (*P(T<=t)* = 0.032) was observed in mean *LAI* of SR during 2015. At the same time, a 21.0% (*P(T<=t)* = 0.140) decrease in average *LAI* of DR stands was observed (*Fig. 3*). In the case of DR, warm weather in 2015 did not further enhance the negative impact resulting from the lack of water cover. Our investigations may be valid for shorter time periods only, as common reed is a wetland's macrophyte demanding fluctuating water cover for a longer time period (*Engloner*, 2009).

There was rather sharp decrease in the maximum *LAI* of DR due to limited water. Declines for DR were 97.1% (*P(T<=t)* = 0.0001) and 100% (*P(T<=t)* = 0.0001) for 2014 and 2015, respectively. When there was unlimited access to water, a 14.4% difference (*P(T<=t)* = 0.045) was found in seasonal peak *LAI*, in favor of the humid season in 2014. Peak *LAI* of the SR stand was intermediate between the results of *Zhou* and *Zhou* (2009) and *Herbst* and *Kappen* (1999) for reed wetland in northeast China (41° 08′ N) and Germany (54° 06′ N), respectively. The maximum *LAI* of the dryland reed stand was much lower than that observed in the literature (close common reed peak *LAI* results were published by *Sun* and *Song* (2008) for Sanjiang Plain, Northeast China, 47°35′N), and it can be attributed to on-site lack of water cover that is not a common and long-lasting occurrence in wetland habitats.

Using temporal variation in *LAI*, we are able to derive the complete seasonal progression of canopy growth dynamics. Thus, *LAI* serves as a suitable metric that quantifies seasonal patterns in plant development (*Savoy* and *Mackay*, 2015).

4.3. Estimation of ET for common reed

An empirical *ET* model developed using meteorological and a plant factor (*LAI*) was able to estimate differences in common reed *ET* rates with altered water supply with reasonable accuracy. Differences were noticed in total *ET* when both water supply and season were assessed. Modeling seasonal *ET* sums of SR showed only a slight increase of 56.3 mm and 50.8 mm in 2014 and 2015, respectively. *ET* total showed significant variation between both seasons, with the *ET* sum of 2015 being almost twice that of 2014 (118.8 mm in DR and 113.3 mm in SR). Changes in weather conditions might be responsible for interannual *ET* variation. *ET* has long been known to vary due to meteorological conditions (*Drexler et al.*, 2008), mainly due to available energy.

The modeled 4.2–5.1 mm of daily mean *ET* rates for common reed at the Kis-Balaton wetland in the current study shows a slightly higher value than the 4.3–4.4 mm daily mean *ET* rates reported by *Irmak et al.* (2013) for 2009 and 2010 and *Lenters et al.* (2011) for 2009 in Nebraska (40°17 ′ N and 41°79 ′ N) at slightly lower latitudes than our study site. During 2014, due to extreme wet weather (and lower air temperatures), total *ET* of 783–842 mm per season was lower than the values reported by *Anda et al.* (2015) according to a 16-year mean on-site *ET* total of 807 mm.

5. Conclusions

Common reed *LAI* was negatively impacted by water limiting conditions, irrespectively of the season. Despite the fact that plants with unlimited access to water showed a similar seasonal trend in leaf growth with common reed standing in water, a significant change in the size of *LAI* was observed. In our two-season study, common reed seemed to be more sensitive to the presence or lack of continuous water cover than to variable seasonal weather conditions.

Comparison of the *GDD*-based estimates for peak *LAI* with measured values showed that the performance of a third-degree polynomial model was acceptable to project maximum *LAI* in two water supply levels. Peak *LAI* was projected between ~1000 °C (wet season) and ~1200 °C (dry season) *GDD* values.

The larger the *LAI* (stand density), the larger the *ET* rates (totals) observed during the two-season monitoring period. In spite of abundant literature about the impact of fluctuating water levels on *ET* and biomass of common reed belts, less information is available about changing architecture (*LAI*) of plants due to variable water conditions. *Ehrenfeld* (2000) stressed the importance of structural alteration of hydro-hygrophilous environments as one of the causes of wetland degradation. Results of our study on common reed *LAI* grown in both wet and dry conditions may contribute to avoid this negative phenomenon of natural wetlands. *LAI* estimates based on meteorological variables may provide useful inputs for *ET* and growth models.

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