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Pre-anthesis development of winter wheat and barley and relationships with grain yield

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ABSTRACT

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The aim of this study was to improve understanding of (1) the effect of genotypic and environmental factors on pre-anthesis development and leaf appearance traits of barley and wheat; (2) the relationship of these factors with grain yield, and (3) the differences between these two crops across different environments/sowing dates. Therefore, trials with six two-row winter barley and six winter wheat cultivars were carried out in two successive growing seasons on four sowing dates. Our study showed that the observed traits varied between species, cultivars and sowing dates. In both growing seasons, biomass at anthesis and grain yield declined almost linearly by delaying the sowing date. There was no clear advantage in grain yield of wheat over barley under conditions of later sowing dates. Generally, barley produced more leaf and had shorter phyllochron than wheat. Both wheat and barley showed a similar relationship between grain yield and different pre-anthesis traits.

Keywords: *Hordeum vulgare*; photoperiod regime; sowing condition; planting time; *Triticum aestivum*

Grain yield (YIL) is formed continually from sowing to maturity (Slafer 2003), but some phases are more significant for determination of the final YIL (Borràs-Gelench et al. 2010). Anthesis date (AD) and pre-anthesis development play a crucial role in determining cultivar adaptation to particular environments (Reynolds et al. 2009). Choosing the appropriate cultivar and sowing date enables the optimization of AD with this narrow optimal window. Along with phenological development, appearance and number of leaves on the main stem are influential factors affecting light interception, dry matter accumulation and crop YIL (Repková et al. 2009). The coordination of final leaf number on the main stem (FLN) and phyllochron (PHY) determines duration of the pre-anthesis period (He et al. 2012).

Under agro-ecological conditions of the Pannonian environments, barley is usually sown in late September and early October (Mirosavljević et al. 2015), while recommended and optimal sowing dates for wheat are mid- and late October (Jaćimović et al. 2013). This is based on the presumption that barley is more sensitive to the negative effect of agro-ecological conditions than wheat, especially when it is sown outside of the recommended sowing period. However, there is not much empirical information comparing the development

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and YIL of both species in the same experiment to confirm this assumption. Although barley and wheat have different physiological strategies in the determination of grain number per unit area and final YIL (Prado et al. 2017), there is less information on comparative pre-anthesis development of these crops, especially in the Pannonian environments. A comparative analysis of variation in the pre-anthesis development and leaf appearance traits (PHY and FLN) of barley and wheat might help explain their performance across different environments or sowing dates. Therefore, the objectives of the this study were to (a) compare YIL and different pre-anthesis traits (PHY, FLN, stem elongation, period from sowing to stem elongation, biomass at AD) in barley and wheat, and (b) identify the role of these traits in the determination of the final YIL under different sowing dates which combine a wide range of temperatures and photoperiod regimes in the field.

MATERIAL AND METHODS

Treatments. The field trial was conducted at the experimental field of the Institute of Field and Vegetable Crops, Novi Sad, Serbia (19°51'E, 45°20'N) during the growing seasons of 2013/2014 and 2014/2015, on non-carbonate Chernozem soil with soybean as the previous crop. The experiment consisted of four target sowing dates (SD1 – late September; SD2 – mid-October; SD3 – late October; SD4 – mid-November), and six winter wheat cultivars (early: Vrn-7 and Prima, medium early: Renesansa and Simonida, and late: NS Ena and NS Metka) and six two-row winter barley cultivars (early: NS 557 and NS 551, medium early: Sonate and Sonja, and late: Cordoba and Greval). SD1 was achieved on 27 September 2013 and 28 September 2014, SD2 on 11 October 2013 and 11 October 2014, SD3 on 25 October 2013 and 27 October 2014, and SD4 on 8 November 2013 and 7 November 2014. The plots (5 m^2) were arranged in a split-plot design with sowing dates as main plots and cultivars as sub-plot treatments in three replications. Sowing density was 350 viable seeds per m^2 for winter barley and 450 viable seeds per m^2 for winter wheat. The plot size was 5 m^2. All trials were fertilized in doses consistent with good agricultural practice, based on the soil agrochemical analysis. Weeds, diseases and pests were controlled by spraying the recommended pesticides.

Measurements. Three plants were labelled in the inner rows of each sub-plot at seedling emergence so as to study the dynamics of leaf appearance. Leaf number on the main stem was measured three times per week, according to the Haun (1973) scale. Phyllochron was calculated as the reciprocal of the slope, of the relationship between the cumulative number of the emerged leaves and thermal time. Further, the following phenological phases were studied: (i) period from sowing to the onset of stem elongation (S-SE); (ii) stem elongation phase (SE-A) period from the onset of stem elongation (BBCH 31) to anthesis (BBCH 61); (iii) grain-filling period (GFP) period from anthesis date to physiological maturity. Onset of stem elongation phase was recorded when the first internode had elongated about 0.5 cm above the ground surface. AD was recorded as the date on which 50% of the spikes in a plot had begun shedding pollen. The stage of physiological maturity was recorded when peduncle and spike lost green colour. Daily maximum (T_{max}) and minimum (T_{min}) air temperatures were obtained from the meteorological station located at the experimental field. Daily mean air temperature was calculated as $T = 0.5 \times (T_{max} + T_{min})$. Duration of the phases was assessed in all trials by calculating thermal time (°C days, using a base temperature of 0°C) between particular stages.

In order to determine the changes of aboveground biomass (BA), plant samples (1 m of a central row) were taken approximately at AD (BBCH 61) and physiological maturity. Samples were dried at 80°C for 48 h before weighing and YIL (t/ha) was adjusted to 14% moisture.

Data analysis. Data were subjected to a combined analysis of variance, treating the sowing date as the main plot and the species as the sub-plot. The cultivars were nested within species. Means were compared using the Tukey's test ($P < 0.05$). Moreover, trait association was analysed by linear regression analysis and correlation analysis. Data analysis was performed using R 3.0.2 (R Development Core Team, Vienna, Austria).

Weather conditions. High precipitation in September and October accompanied by favourable temperatures enabled rapid emergence and early growth in 2013/2014. Winter period was characterized by mild temperatures and extreme

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drought. The cultivars continued their development under favourable weather conditions in spring. Weather conditions in 2014/2015 were characterized by higher level of precipitation during winter period and grain filling period, while the spring precipitation was more equally distributed than in 2013/2014. Under these weather conditions, cultivars had more vigorous growth which resulted in higher BA in relation to 2013/2014. In both growing seasons, excessive rainfall and average temperatures accompanied grain development in May, especially in 2014/2015 (Figure 1).

RESULTS AND DISCUSSION

The results from our study showed that on average, barley produced more leaves and had faster leaf appearance compared to wheat in both growing seasons (Table 1). In both growing seasons, late cultivars of wheat and barley produced more leaves than other cultivars within each species. The shortest PHY among barley cultivars was recorded in late cultivars (Cordoba and Greval). On the other hand, late maturity wheat cultivars NS Ena and NS Metka had the highest value of PHY. These results confirm the findings of Giunta et al. (2015) who reported that barley produces more leaf and has shorter PHY than wheat and therefore is more appropriate for dual-purpose cropping. The highest FLN and PHY in wheat and barley were obtained by sowing in SD1 and SD2. The variation in vernalisation and photoperiod due to the influence of different sowing dates had a significant influence on the FLN (Giunta et al. 2015). In earlier sowing dates, moderate temperature in autumn caused higher leaf initiation rate and a slower vernalisation progress. On the other hand, late sowing led to lower leaf initiation rate and vernalisation requirements were more rapidly satisfied (Kirby et al. 1985), and such conditions resulted in lower leaf production and shorter PHY.

On average, the duration of S-SE cycle in winter wheat was longer than in two-rowed barley cultivars in each growing season. Among the cultivars, late maturity winter wheat cultivars had the longest duration of this period, while the shortest duration of S-SE was recorded in the barley cv. NS 557 in 2013/2014 and the cv. Greval in 2014/2015. The S-SE phase also varied between the sowing dates, being shorter in later sowings than in earlier ones.

Generally, wheat cultivars had shorter duration of the SE-A period than barley. Furthermore, for both species, late cultivars had the longest duration of the SE-A phase. Also, the duration of the SE-A period was influenced by the sowing date, and the duration of SE-A decreased with delayed sowing in both growing seasons. In both growing seasons, wheat had longer duration of grain filling period. The cv. Renesansa could be highlighted as the genotype with the highest values of this trait. In 2014, the late barley cv. Cordoba had the shortest duration of GFP, while in the next season the shortest GFP was recorded in early cv. NS 551. The duration of GFP significantly decreased as the sowing date was delayed.

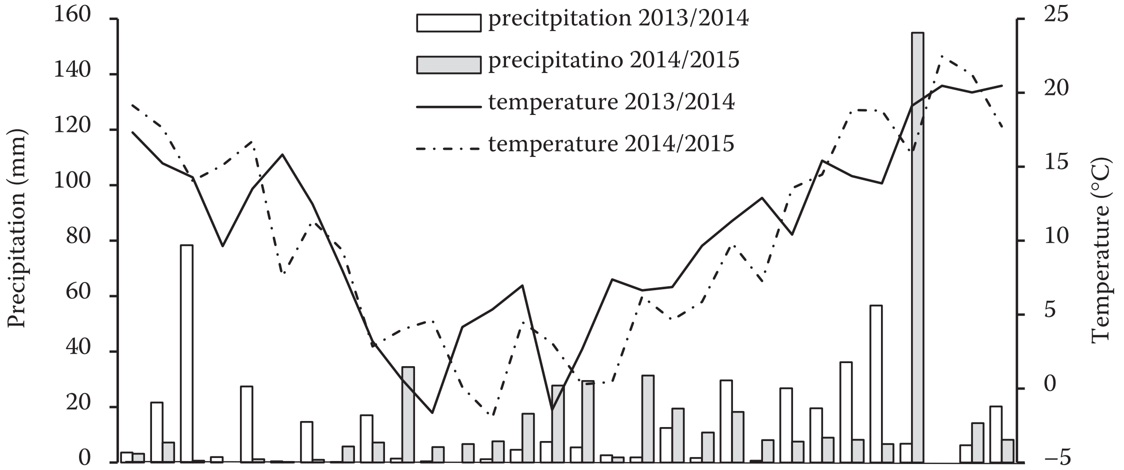

Figure 1. Ten-day period average temperature and precipitation for the 2013/2014 and 2014/2015 growing seasons

Table 1. Final leaf number (FLN); phyllochron (PHY); period from sowing to stem elongation (S-SE); stem elongation period (SE-A); grain filling period (GFP); biomass at anthesis (BA) and grain yield (YIL) of wheat and barley in four sowing dates in 2013/2014 and 2014/2015

Treatment	2013/2014							2014/2015						
	FLN	PHY (°C day/leaf)	S-SE	SE-A	GFP	BA	YIL	FLN	PHY (°C day/leaf)	S-SE	SE-A	GFP	BA	YIL
			(°C day)			(t/ha)				(°C day)			(t/ha)	
Barley	13.7^{a}	88.6^{b}	329^{b}	903^{a}	724^{b}	8.89^{b}	7.0^{a}	12.9^{a}	84.0^{b}	361^{b}	1011^{a}	734^{b}	10.4^{a}	9.3^{a}
NS 557	12.4^{ef}	87.4^{de}	323^{d}	845^{d}	787^{bcd}	7.2^{e}	6.3^{c}	11.7^{cd}	83.9^{ef}	378^{abc}	913^{ef}	730^{ef}	8.1^{f}	7.4^{e}
NS 551	11.8^{f}	92.8^{bc}	326^{d}	828^{d}	779^{cde}	7.3^{e}	6.5^{c}	11.4^{cde}	88.1^{de}	357^{abc}	902^{f}	718^{f}	8.7^{ef}	7.9^{de}
Sonate	13.4^{cd}	93.1^{bc}	335^{bcd}	893^{c}	706^{ef}	9.3^{c}	6.7^{bc}	12.7^{b}	85.2^{ef}	387^{abc}	996^{bc}	742^{def}	9.8^{c}	9.0^{bc}
Sonja	14.2^{bc}	87.8^{de}	327^{d}	922^{b}	678^{f}	9.1^{c}	7.6^{a}	13.5^{a}	83.3^{f}	348^{bc}	1016^{b}	721^{ef}	11.7^{b}	9.6^{b}
Cordoba	14.9^{ab}	85.6^{e}	330^{cd}	964^{a}	665^{f}	9.2^{c}	7.2^{ab}	14.1^{a}	81.1^{f}	356^{abc}	1113^{a}	767^{cde}	11.6^{b}	10.8^{a}
Greval	15.4^{a}	85.1^{e}	332^{cd}	969^{a}	729^{def}	11.3^{a}	6.7^{bc}	13.7^{a}	82.6^{f}	342^{c}	1123^{a}	728^{ef}	12.6^{a}	11.1^{a}
SD1	14.9^{a}	94.8^{b}	349^{bc}	1030^{a}	792^{bc}	10.1^{b}	7.4^{ab}	14.4	91.0^{b}	388^{abc}	1166^{a}	778^{b}	12.9^{a}	10.7^{a}
SD2	14.0^{b}	94.5^{b}	336^{cd}	955^{c}	736^{cd}	9.2^{c}	7.6^{a}	13.3	89.4^{b}	362^{cd}	1099^{b}	738^{c}	11.3^{b}	9.8^{a}
SD3	13.5^{b}	83.9^{c}	320^{de}	874^{d}	702^{de}	8.5^{d}	6.6^{cde}	11.9	81.0^{d}	351^{cd}	961^{d}	721^{cd}	9.9^{c}	8.7^{cd}
SD4	12.3^{cd}	81.4^{c}	312^{e}	755^{f}	666^{e}	7.8^{e}	6.4^{de}	11.9	74.8^{e}	344^{d}	816^{f}	701^{d}	7.6^{e}	8.1^{d}
Wheat	12.1^{b}	96.1^{a}	356^{a}	868^{b}	850^{a}	9.2^{a}	6.8^{a}	11.7^{b}	93.1^{a}	389^{a}	946^{b}	831^{a}	9.7^{b}	8.8^{b}
Vrn-7	10.9^{g}	94.9^{b}	354^{abc}	824^{d}	849^{abc}	8.4^{d}	6.7^{bc}	11.0^{e}	90.7^{cd}	377^{abc}	911^{ef}	779^{cd}	9.7^{cd}	9.0^{bc}
Prima	11.7^{f}	91.8^{bcd}	347^{abcd}	827^{d}	858^{ab}	8.3^{d}	6.9^{bc}	11.0^{de}	90.7^{cd}	392^{abc}	901^{f}	838^{ab}	9.4^{cde}	8.2^{cde}
Renesansa	12.3^{ef}	89.7^{cde}	358^{ab}	875^{c}	907^{a}	9.4^{c}	7.3^{ab}	11.6^{cde}	90.7^{cd}	387^{abc}	946^{de}	875^{a}	9.9^{c}	9.5^{b}
Simonida	12.2^{ef}	94.9^{b}	353^{abc}	885^{c}	859^{ab}	10.3^{b}	7.6^{a}	11.8^{c}	92.7^{bc}	374^{abc}	951^{d}	850^{a}	11.2^{b}	9.7^{b}
NS Ena	12.7^{de}	101.4^{a}	363^{a}	893^{bc}	824^{bc}	9.4^{c}	6.2^{c}	12.1^{bc}	97.0^{a}	406^{a}	976^{cd}	842^{b}	9.3^{cde}	8.3^{cde}
NS Metka	12.8^{de}	104.2^{a}	364^{a}	903^{c}	804^{bcd}	9.3^{c}	6.3^{c}	12.6^{b}	96.9^{ab}	399^{ab}	995^{bc}	801^{bc}	8.9^{def}	8.1^{cde}
SD1	13.7^{b}	99.5^{a}	382^{a}	998^{b}	908^{a}	10.8^{a}	7.5^{a}	13.2^{b}	98.2^{a}	418^{a}	1116^{b}	859^{a}	12.3^{a}	9.5^{b}
SD2	12.7^{c}	99.4^{a}	367^{ab}	944^{c}	840^{b}	10.1^{b}	6.8^{cd}	12.0^{c}	99.6^{a}	408^{ab}	1036^{c}	831^{a}	10.0^{c}	9.3^{bc}
SD3	11.9^{d}	93.3^{b}	350^{bc}	818^{e}	834^{b}	8.8^{cd}	6.9^{bc}	11.2^{d}	86.3^{c}	382^{abcd}	897^{e}	829^{a}	9.2^{d}	9.2^{bc}
SD4	10.3^{e}	92.4^{b}	327^{de}	711^{g}	819^{b}	7.0^{f}	6.3^{e}	10.3^{e}	84.6^{c}	376^{bcd}	766^{g}	825^{a}	7.8^{e}	8.0^{d}

Different letters represent significant differences between cultivars ($P < 0.05$). SD1 – late September; SD2 – mid-October; SD3 – late October; SD4 – mid-November

Total biomass at AD (BA) in 2013/2014 was slightly higher in wheat than in barley, while in the following growing season barley produced higher BA. In both growing seasons among barley cultivars, the late cv. Greval produced the highest BA, while in wheat the highest BA was recorded in the medium early cv. Simonida. By delaying the sowing date from late September (SD1) to mid-November, BA was reduced almost linearly. Overall, there was a significant positive relationship between FLN and BA, while no association was found between BA and PHY (Figure 2).

Results showed that the grain yield (YIL) varied between species, cultivars and sowing dates. In 2013/2014 there was no difference in YIL between wheat and barley, while in the following season barley produced higher average YIL than wheat. Among barley cultivars, the highest YIL was recorded in Greval, while Simonida was the highest yielding wheat cultivar. In both growing

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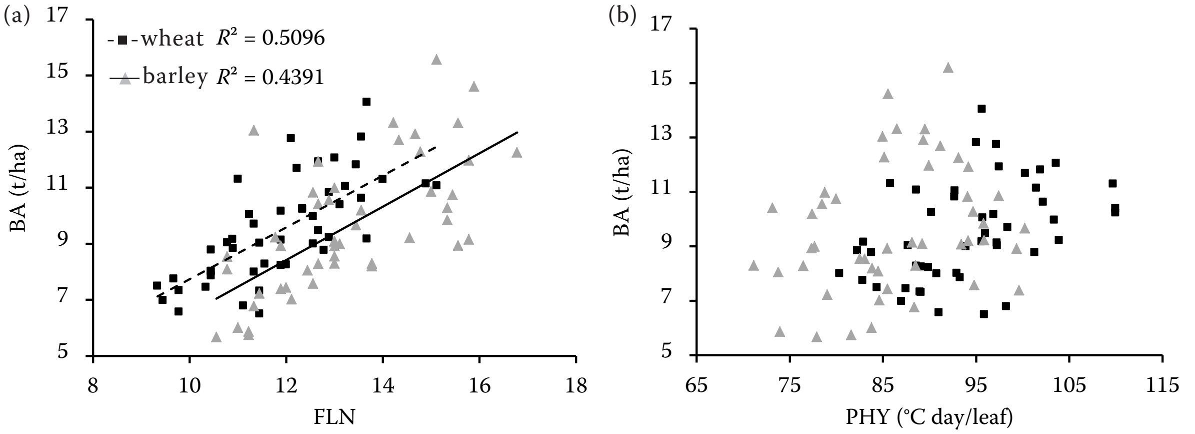

Figure 2. Relationship between biomass at anthesis (BA) and (a) final leaf number (FLN) and (b) phyllochron (PHY)

seasons, YIL declined by delaying the sowing date in both species. Additionally, this study found no clear advantage of wheat over barley under late sowing conditions. Therefore, our data do not confirm the widely spread assumption among farmers that wheat has better YIL performance, especially when it is sown in early November. However, higher variation in YIL between cultivars than between species indicates that farmers should pay more attention to cultivar selection, regardless of the sowing date.

Different levels of correlations between pre-anthesis traits and YIL were observed in barley and

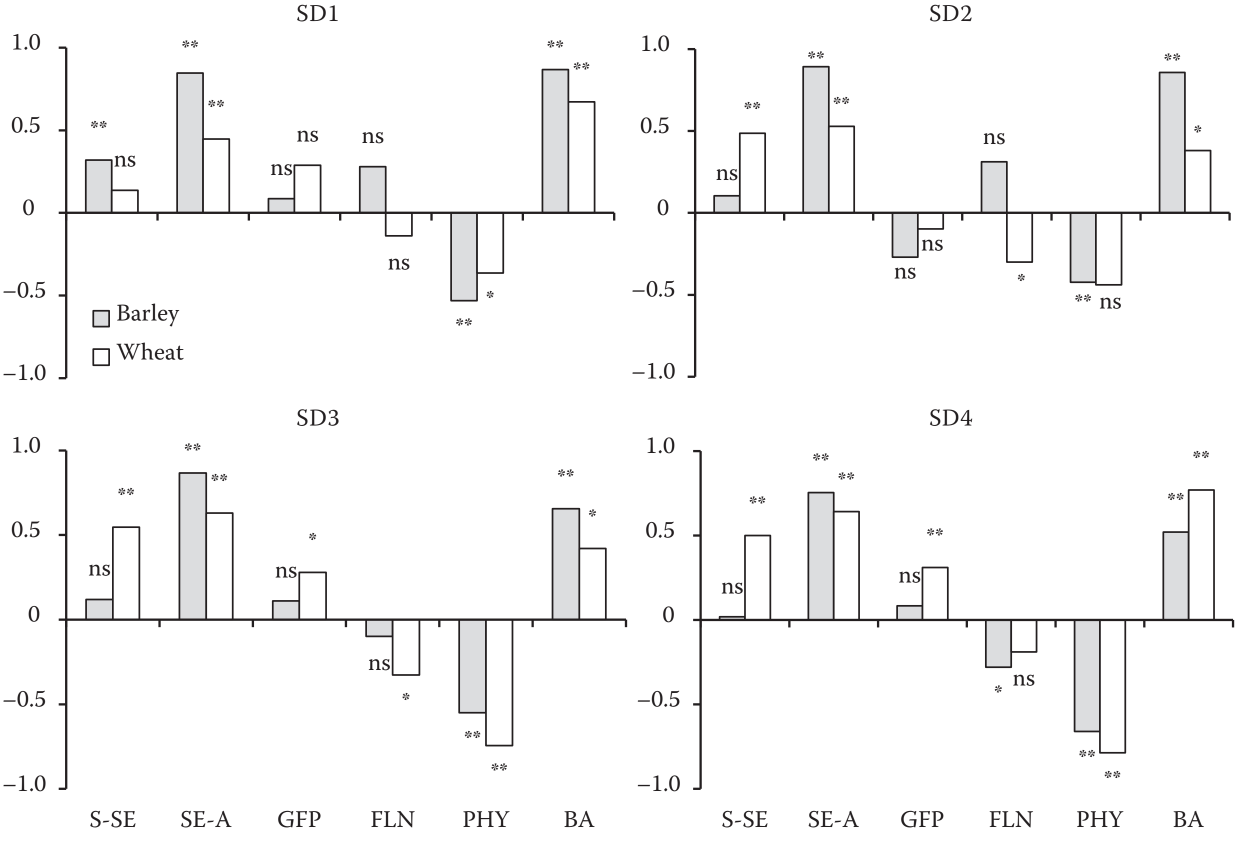

Figure 3. Correlation between grain yield and pre-anthesis traits (S-SE – period form sowing to stem elongation; SE-A – stem elongation period; GFP – grain filling period; FLN – final leaf number per main stem; PHY – phyllochron; BA – biomass at anthesis) in wheat and barley in four sowing dates averaged across growing seasons (SD1 – late September; SD2 – mid-October; SD3 – late October; SD4 – mid-November). ns – not significant

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wheat (Figure 3). The degree of correlation also varied with the sowing date. YIL was negatively associated with the duration of PHY in barley and wheat for each sowing date, while the correlation between YIL and FLN was not significant. PHY and FLN correlation with YIL could be explained by their association with leaf area development and AD. As previously reported, leaf area index is closely related with YIL (Ayeneh et al. 2002). Shortening the period between appearance of two successive leaves and increase of FLN (Valle and Calderini 2010) hastens canopy closure and improves leaf area index and the radiation interception during early vegetative development (Foulkes et al. 2009). Further, by simultaneously shortening PHY and increasing FLN, a cultivar may have higher leaf area development without modification of AD. Therefore, increase in FLN, followed by decrease in PHY, could be a potential approach for improvement of leaf area and prolongation of SE-A and further grain number and yield improvement (Martre et al. 2015).

In each sowing date, the duration of SE-A had a significant positive relationship with YIL both in wheat and barley. Correlation between S-SE and YIL was significant in wheat for three sowing dates, while in barley the relationship between these two traits was positive for each sowing date, but not statistically significant. Accordingly, the prolongation of the SE-A phase should represent an important strategy to increase YIL in these species. Extending the SE-A increases grain number per unit area and YIL by improving assimilates availability and florets survival (Fischer 2007). Because AD represents a key adaptive trait that was optimized through breeding programs (Fischer 2011), lengthening the duration of the SE-A phase should be achieved without modifying AD. Moreover, there was no significant relationship between GFP and YIL in wheat or barley, indicating that the rate of synthesis of storage products in the growing grain is more important than the duration of this period in final grain weight (Xie et al. 2015) and YIL determination (Brdar-Jokanovic et al. 2006).

BA was positively correlated with YIL for each sowing date. Crop development and biomass accumulation during pre-anthesis period were positively correlated with final YIL (Křen et al. 2014). BA reduced almost linearly as the sowing date was delayed from SD1 to SD4. Variations in BA, due to different sowing dates, are also results of the change in duration of the period to AD (Ehdaie and Waines 2001). Assimilates stored in vegetative parts during the period to AD are important for maintenance of YIL when the process of photosynthesis is reduced by different abiotic factors (Dordas 2012). Furthermore, as the result of breeding progress, modern wheat and barley cultivars reached already high values of harvest index and genetic improvement cannot be a result of further increase of the harvest index (Foulkes et al. 2009). Therefore, increasing biomass with maintaining or even improving the harvest index is one of the potential goals in cereal breeding.

In conclusion, our study showed that there was no clear advantage of wheat over barley across different sowing dates, and disproves the assumption that wheat has better YIL performance than barley when sown after the recommended period. Reduction in final YIL in the late sowing was the result of a significant change in BA and crop development. Both wheat and barley showed a similar relationship between YIL and different pre-anthesis traits. Increasing BA accumulation during the pre-anthesis period and prolonging the duration of the SE-A should represent potential strategies for further YIL improvement in these species.

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