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Sole and combined effects of drought and phosphorus application on soybean

Az aszály és a foszfor kijuttatásának egyedüli és együttes hatása a szójababra

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ABSTRACT

Phosphorus is one of the most important macronutrients for plant development, and although it might be present in relatively high concentrations in the soil, yet the readily-available amounts can be much lower because it presents in forms of soil complexes. P application can help plants tolerate drought stress, which is increasingly reported and predicted in soybean main cultivation areas. An experiment was carried out in 2018 and 2019 in Debrecen, Hungary to investigate the sole and combined effects of P fertilization and drought stress on two soybean cultivars. Results showed that leaf area, relative chlorophyll content and, to a higher extent, stomatal conductance and plant height of both cultivars were negatively affected by both P and water deficits. Pod number/plant and seed yield were also decreased as a result of drought and lack of P. Moreover, oil concentration in the produced seeds was measurably decreased under drought stress and significantly increased with P application, whereas protein concentration was not measurably affected by P application, but increased under drought stress conditions. It could be concluded that the high rate of P fertilizer is not recommended in the study area as it did not have noticeable effects compared to the lower rate.

Keywords: fertilization, seed quality, soybean, water deficit, yield

ABSZTRAKT

A foszfor az egyik legfontosabb makrotápanyag a növény fejlődésében, és bár a talajban viszonylag magas koncentrációban lehet jelen, mégis a rendelkezésre álló mennyiségek sokkal alacsonyabbak lehetnek, mivel talajkomplexek formájában jelenik meg. A P alkalmazás segíthet a növényeknek elviselni az aszálystresszt, amelyet a szójabab legfontosabb termesztési területein egyre inkább jelentenek és előrejelznek. 2018-ban és 2019-ben kísérletet végeztünk Debrecenben, Magyarországon a P-műtrágyázás és az aszálystressz egyedüli és kombinált hatásainak vizsgálatára két szójababfajtára. Az eredmények azt mutatták, hogy mindkét fajta levélterületét, a relatív klorofilltartalmat, és nagyobb mértékben a sztóma vezetőképességét és a növénymagasságot mind a P, mind a vízhiány negatívan befolyásolja. Az aszály és a P. hiánya miatt a növényenkénti hüvelyszám és a vetőmag hozamai szintén csökkentek. Ezen túlmenően az előállított vetőmagok olajkoncentrációja szárazsági stressz alatt mérhető módon csökkent, és a P alkalmazásával jelentősen megnőtt, míg a fehérjekoncentrációt a P nem befolyásolta alkalmazás, de szárazság-stressz körülmények között fokozódott. Megállapítható, hogy a magas P-műtrágyamennyiség nem javasolt a vizsgálati területen, mivel az alacsonyabb arányhoz képest nem volt észlelhető hatás.

Kulcsszavak: műtrágyázás, szójabab, termés, vetőmagminőség, vízhiány

INTRODUCTION

Phosphorus (P) is one of the most important mineral nutrients for plant development and energy conservation and transfer (Abel et al., 2002; Elser et al., 2007). In addition, P has a vital role in photosynthesis and chloroplast composition (Hernández and Munné-Bosch, 2015). Considerable amounts of P, in the form of ATP, are needed for biological N_2-fixation process by the nodules in legume plants (Xavier and Germida, 2002), and increasing P rate resulted in adequate increase in seed-N resulting from N_2-fixation stimulation as reported by Ogoke et al. (2003). It was previously reported that P application increased the dry matter, biomass and, consequently, the yield of soybean plants (Andraski et al., 2003; Cai et al., 2004; Dong, 2009). Not only quantity, but also seed quality was reported to be improved by P application (Shahid et al. 2009).

Although soil might have high concentrations of P, yet most of it can be unavailable for plants due to its poor solubility and fixation (Smith et al., 2011; Mahanta et al., 2014). As a result, N_2-fixation rate in legumes and, consequently, the advantage of this ecologically friendly process can be decreased (Sulieman et al., 2013). P deficiency can also decrease seedling vigor and root development (Jin et al., 2006). As such, soybean plants that were subjected to drought stress conditions during reproductive stages but received P fertilizer had better root morphology, better P uptake and, as a result, better yield (Jin et al., 2005).

Soybean (*Glycine max* (L.) Merrill) is the most grown seed legume worldwide, providing an inexpensive source of protein and oil (Hao et al., 2013; Cerezini et al., 2016). Soybean has high requirements of available P (10-15 mg/kg soil) (Aune and Lal, 1997), and low soil-P availability limits the soybean yields (Xu et al., 2003). However, excessive amounts of P resulted in growth inhibition in soybean (Cai et al., 2004), in addition to the fact that only 10%–45% of P- fertilizer added to the soil is readily usable (Adesemoye and Kloepper, 2009).

Drought stress is considered as one of the most hazardous abiotic stresses that affects soybean production stability (Manavalan et al., 2009), and reports predict increased drought frequencies and intensities (Turner et al., 2011). However, P application was reported to enhance drought stress tolerance (Boem and Thomas, 1998; Singh and Sale, 2000). Jin et al. (2006) shortlisted 3 explanations for this enhancement; 1- energy produced by photosynthesis and carbohydrate metabolism is stored in P compounds, and this stored energy has a role in drought tolerance (Jones et al., 2003); 2- P enhances water extraction by roots (Singh et al., 1997) and water conservation in the plant tissues (Garg et al., 2004); 3- P increases the soluble proteins under drought stress conditions by enhancing nitrogen metabolism (Al-Karaki et al., 1996).

Although many previous work on the sole effect of P fertilizer and the drought stress on different crops is already available in the literature, not much published work that deal with the combined effect of P nutrition and drought on soybean in the study area could be found, especially that soybean is newly entered in the crop rotations in the area, so this study aimed at monitoring the sole and combined effects of P fertilization and drought stress on two soybean cultivars in Debrecen, Hungary.

MATERIALS AND METHODS

Two soybean cultivars (Pannonia Kincse and Boglár, Bonefarm, Hungary) were sown in Debrecen University's experimental site (Látókép) (N. latitude 47° 33', E. longitude 21° 27') on April 23rd and 26th, and were harvested on September 15th and 16th in 2018 and 2019, respectively. The seed rate was 90 kg/ha for both cultivars. The soil type is calcareous chernozem with the following agrochemical properties; pH: 6.41, OM: 2.46%, N: 3.97 ppm, P_2O_5: 90.7 ppm, K_2O: 206.7 ppm. Precipitation amounts during the vegetative period were 266 mm in 2018 and 281 mm in 2019. The experimental design was split-split plot design, with cultivars being the main plots, irrigation regimes being the sub-plots and P fertilization rates being the sub-sub-plots. Three P-fertilizer rates; 0, 45 and 90 kg/ha P_2O_5 (0P, 45P and 90P, respectively) were applied manually (in the form of single superphosphate) under two irrigation regimes; drought stress regime (accounting only on the precipitation as the only source of water supply) and irrigated regime (where, in addition to precipitation, a total of 100 mm of irrigation water was applied). Each treatment consisted of three replications.

Stomatal conductance (g_s) was measured using AP4 porometer (Delta-t devices, UK). LAI (Leaf Area Index) values were recorded using SS1 – SunScan canopy analysis system (Delta- T Devices, UK). Relative chlorophyll content (in the form of SPAD) (Soil Plant Analysis Development) was measured using SPAD-502Plus (Konica Minolta, Japan). 10 randomly-selected plants from the middle rows of each plot were used for the mentioned traits. All traits were measured at four different stages of soybean's life cycle (Fehr and Caviness, 1977); fourth node (V4), full bloom (R_2), full pod (R4) and full seed (R6).

Pod number per plant was counted at R4 stage. Plant height was measure at R6 stage using a standard ruler. 10 randomly-selected plants from the middle rows of each plot were used for the mentioned traits.

Seed yield was calculated by harvesting the middle 4 rows of each plot and adjusting the yield to 13% moisture content. Both protein and oil concentrations were determined using NIR analyser Granolyser (Pfeuffer, Germany).

SPSS software was run to analyze and compare the means (ANOVA) and to indicate the effect size (by means of Partial Eta Squared), followed by Tukey post-hoc test to indicate the statistically-different means, and Pearson's correlation to indicate correlation coefficient (IBM SPSS ver. 26, USA software). All data presented and analyzed are means of the two years of experiment.

RESULTS

Stomatal Conductance (g_s)

In the two studied cultivars, both irrigation and fertilization treatments had highly-significant effect on gs, whereas their interaction did not.

In both cultivars, and regardless of irrigation regime, 45P treatment increased g_s (by 9.0 and 6.0% for Pannonia Kincse and Boglár, respectively) compared to 0P. 90P treatment, on the other hand, had higher g_s than 0P, but not 45P (tables 1 and 2). The effect size of fertilization on g_s in Pannonia Kincse cultivar was estimated as 34.1; i.e. 34.1% of changes in g_s are the result of the different fertilization rates. In Boglár cultivar, on the other hand, the effect size was estimated as 29.9%. However, the correlation between g_s and fertilization was slight and insignificant (tables 3 and 4).

Drought significantly decreased gs in all fertilization treatments of both cultivars. The average reduction was 45.9 and 50.7% for Pannonia Kincse and Boglár, respectively (tables 1 and 2). Irrigation was responsible for 97.2 and 98.7% of changes in g_s in Pannonia Kincse and Boglár, respectively. In addition, the correlation coefficient between gs and irrigation was highly significant in both cultivars (tables 3 and 4).

Relative Chlorophyll Content (SPAD)

The effect of fertilization was highly-significant on Pannonia Kincse and significant on Boglár cultivar, whereas the effect of irrigation was only highly-significant on Pannonia Kincse. The interaction of fertilization and irrigation had no significant effect on both cultivars.

45P enhanced SPAD values in both cultivars compared to 0P, regardless of irrigation regime; however, the differences were insignificant. 90P did not further enhance SPAD values compared to 45P counterparts for both cultivars and under both irrigation regimes (tables 1 and 2). 29.6 and 21.4% of differences in SPAD were attributed to fertilization effect in Pannonia Kincse and Boglár, respectively. The correlation with fertilization was significant in both cultivars (tables 3 and 4).

Drought stress decreased SPAD values by an average of 2.5 and 1.3% for Pannonia Kincse and Boglár, respectively; however, the reductions were insignificant (tables 1 and 2). 28.0% of differences in this trait were a result of drought stress in Pannonia Kincse, but only 4.0% in the case of Boglár cultivar.

Table 1. The effect of drought stress on stomatal conductance (g_s) (mmol/m^2/s), relative chlorophyll content (SPAD), leaf area index (LAI) and plant height (cm) of soybean cv. Pannonia Kincse under different P-fertilizer rates

Trait	Irrigation regime	0P	45P	90P	Average
g_s	Drought-stressed	201.7^{2}	227.8^{2}	221.8^{2}	217.1
	Irrigated	393.3^{ab1}	420.7^{a1}	389.2^{b1}	401.1
	Average	297.5	324.3	305.5	309.1
SPAD	Drought-stressed	42.2	43.4	43.0	42.9
	Irrigated	43.0	44.6	44.4	44.0
	Average	42.6	44.0	43.7	43.4
LAI	Drought-stressed	5.3	6.1	6.0	5.8
	Irrigated	5.9	6.7	6.8	6.5
	Average	5.6	6.4	6.4	6.1
Plant height	Drought-stressed	70.7^{b2}	82.3^{a2}	79.8^{a2}	77.6
	Irrigated	82.0^{b1}	97.3^{a1}	95.7^{a1}	91.7
	Average	76.3	89.8	87.8	84.6

- In each trait, different letters indicate significant differences at .05 level among fertilization treatments within certain irrigation regime
- In each trait, different numbers indicate significant differences at .05 level between irrigation regimes within certain fertilization treatment
- 0P: 0 kg/ha P fertilizer, 45P: 45 kg/ha P fertilizer, 90P: 90 kg/ha P fertilizer

Table 2. The effect of drought stress on stomatal conductance (g_s) (mmol/m^2/s), relative chlorophyll content (SPAD), leaf area index (LAI) and plant height (cm) of soybean cv. Boglár under different P-fertilizer rates

Trait	Irrigation regime	0P	45P	90P	Average
g_s	Drought-stressed	176.8^{2}	194.7^{2}	195.5^{2}	189.0
	Irrigated	375.7^{1}	391.2^{1}	383.7^{1}	383.5
	Average	276.3	292.9	289.6	286.3
SPAD	Drought-stressed	36.8	37.9	37.7	37.5
	Irrigated	36.9	38.6	38.4	38.0
	Average	36.8	38.2	38.0	37.7
LAI	Drought-stressed	4.7	5.5	5.6	5.2
	Irrigated	5.1	5.9	6.2	5.7
	Average	4.9	5.7	5.9	5.5
Plant height	Drought-stressed	69.5^{b2}	74.7^{a2}	75.8^{a2}	73.3
	Irrigated	76.8^{b1}	85.5^{a1}	88.8^{a1}	83.7
	Average	73.2	80.1	82.3	78.5

- In each trait, different letters indicate significant differences at .05 level among fertilization treatments within certain irrigation regime
- In each trait, different numbers indicate significant differences at .05 level between irrigation regimes within certain fertilization treatment
- 0P: 0 kg/ha P fertilizer, 45P: 45 kg/ha P fertilizer, 90P: 90 kg/ha P fertilizer

Leaf Area Index (LAI)

Both fertilization and irrigation treatments significantly affected this trait in Pannonia Kincse, whereas fertilization highly-significantly affected this trait in Boglár cultivar, however, the irrigation effect was insignificant. Moreover, both cultivars were not affected by the interaction of fertilization and irrigation.

Except for a slight decrease in 90P of Pannonia Kincse plants compared to 45P under drought stress, increasing P fertilizer rate was accompanied with increasing LAI values for both cultivars, regardless of irrigation regime. All the differences, however, were insignificant (tables 1 and 2). The effect size of the fertilization on LAI was estimated as 21.5 and 29.1% in Pannonia Kincse and Boglár, respectively.

LAI values were reduced as a result of drought stress application, regardless of cultivar and fertilization treatment. The average reduction caused by drought was 10.8 and 8.8% for Pannonia Kincse and Boglár, respectively. In this trait as well the differences between the two irrigation regimes were insignificant (tables 1 and 2). 17.9 and 11.4% of changes in LAI were resulted from drought stress in Pannonia Kincse and Boglár, respectively. Only in Pannonia Kincse was the correlation coefficient between LAI and irrigation significant (table 3).

Plant Height

Highly significant effects of both fertilization and irrigation were estimated in both cultivars, whereas the fertilization*irrigation effect was significant in Boglár only.

P-fertilizer application, under both irrigation regimes, significantly increased plant height in both cultivars compared to non-fertilized counterpart. However, increasing the fertilization rate (90P) had no significant effect on this trait compared to the lower rate (45P); it slightly increased the plant height of Boglár cultivar, but decreased it in Pannonia Kincse cultivar (tables 1 and 2). 88.3 and 79.3% of differences in plant height in Pannonia Kincse and Boglár, respectively were attributed to different fertilization rates, with a highly significant correlation coefficient (tables 3 and 4).

Regardless of fertilization treatment, drought stress significantly decreased the plant height of both cultivars; the average reduction was 15.4 and 12.4% in Pannonia Kincse and Boglár, respectively (tables 1 and 2). Drought stress was responsible for 91.4 and 87.2% changes in the plant height of Pannonia Kincse and Boglár, respectively. In addition, the plant height of both cultivars was highly-significantly correlated with irrigation treatments (tables 3 and 4).

Pod Number/Plant

The effect of fertilization on this trait was highly significant in both cultivars, whereas irrigation's effect was highly significant in the case of Pannonia Kincse, and significant in the case of Boglár. However, the interaction of irrigation and fertilization did not have any significance, regardless of cultivar.

Under both irrigation regimes, pod number/plant in both cultivars was lower in non-fertilized plots compared to fertilized counterparts; however, the reduction was insignificant (except for drought-stressed, non-

Table 3. Correlation coefficient of irrigation and fertilization treatments with stomatal conductance (g_s), relative chlorophyll content (SPAD), leaf area index (LAI), plant height (PH), pod number/plant (PN), yield, protein concentration (PC) and oil concentration (OC) of soybean cv. Pannonia Kincse

Treatment	g_s	SPAD	LAI	PH	PN	Yield	PC	OC
Irrigation	.977**	.461**	.382*	.740**	.848**	.752**	-.534**	.188
Fertilization	.035	.364*	.376*	.491**	.339*	.505**	.015	.815**

- **. Correlation is significant at the 0.01 level (2-tailed)
- *. Correlation is significant at the 0.05 level (2-tailed)

fertilized treatment of Boglár, where the reduction was significant) (tables 5 and 6). Fertilization rates had an effect percentage of 48.2 and 59.4% of the pod number/plant of Pannonia Kincse and Boglár, respectively. The correlation coefficient of this trait with fertilization was significant, and higher for Boglár compared to Pannonia Kincse (tables 3 and 4).

Although drought reduced pod number/plant in both cultivars, yet its effect was more measurable on Pannonia Kincse, where the reduction was significant, regardless of fertilization treatment (table 5). In Boglár, however, pod number/plant was significantly lower in 0P treatment, whereas the difference was slight and insignificant in both 45P and 90P treatments (table 6), leading to a conclusion that P-fertilizer application could partly ameliorate the negative effect of drought stress on this trait by decreasing the reduction level of pods resulting from exposure to drought. 83.4 of differences in this trait were attributed to drought stress application on Pannonia Kincse cultivar, which was considerably higher that the effect of drought stress application on Boglár cultivar where the effect size was estimated as 12.9%. This conclusion was supported by the higher correlation coefficient of this trait with irrigation treatments in the case of Pannonia Kincse compared to Boglár cultivar (tables 3 and 4).

Yield

Regardless of cultivar, both irrigation and fertilization treatments, but not their interaction, had highly significant effects on the final seed yield. The correlation of both treatments with the yield was also highly significant in both cultivars.

Fertilization, regardless of rate, significantly increased the final seed yield of both cultivars and under both irrigation regimes. However, 90P did not result in any further yield increase compared to 45P counterpart under drought stress conditions, whereas it slightly increased the yield under irrigated regime in both cultivars (tables 5 and 6). 73.3 and 67.6% of changes in the final seed yield were attributed to the different rate of fertilization in Pannonia Kincse and Boglár, respectively.

The final seed yield was significantly decreased by drought, regardless of cultivar and fertilization treatment. On average, Pannonia Kincse and Boglár had 13.5 and 12.5% less yield, respectively as a result of drought stress (tables 5 and 6). Drought stress was estimated to be responsible for 83.6 and 68.0% of the differences of the final seed yield of Pannonia Kincse and Boglár, respectively.

Protein Concentration

Irrigation had highly significant effect on protein concentration in both cultivars; moreover, the correlation between protein concentration and irrigation treatments was significantly negative, i.e. increasing irrigation water amount was accompanied by decreasing protein concentration (tables 3 and 4). In other words; drought stress increased protein concentration, which is demonstrated in tables5 and 6. Fertilization, on the other hand, had relatively low effect on this trait, with a non-significant correlation (tables 3 and 4).

Compared to 0P treatment, 45P treatment resulted in relatively higher protein concentration, regardless of cultivar and irrigation regime.

Table 4. Correlation coefficient of irrigation and fertilization treatments with stomatal conductance (g_s), relative chlorophyll content (SPAD), leaf area index (LAI), plant height (PH), pod number/plant (PN), yield, protein concentration (PC) and oil concentration (OC) of soybean cv. Boglár

Treatment	g_s	SPAD	LAI	PH	PN	Yield	PC	OC
Irrigation	.991**	.176	.288	.753**	.230	.637**	-.913**	.577**
Fertilization	.055	.357*	.488**	.543**	.661**	.569**	.015	.669**

**. Correlation is significant at the 0.01 level (2-tailed)
*. Correlation is significant at the 0.05 level (2-tailed)

Table 5. The effect of drought stress on pod number (/plant), yield (t/ha), protein concentration (%) and oil concentration (%) of soybean cv. Pannonia Kincse under different P-fertilizer rates

Trait	Irrigation regime	0P	45P	90P	Average
Pod number	Drought-stressed	39.0^{2}	40.7^{2}	40.8^{2}	40.1
	Irrigated	43.2^{b1}	45.3^{a1}	45.9^{a1}	44.8
	Average	41.1	43.0	43.3	42.5
Yield	Drought-stressed	4.0^{b2}	4.7^{a2}	4.7^{a2}	4.5
	Irrigated	5.0^{b1}	5.3^{a1}	5.5^{a1}	5.2
	Average	4.5	5.0	5.1	4.9
Protein concentration	Drought-stressed	39.1	39.2	40.0^{1}	39.5
	Irrigated	37.8	38.4	37.0^{2}	37.7
	Average	38.5	38.8	38.5	38.6
Oil concentration	Drought-stressed	20.4^{c}	21.6^{b}	23.1^{a}	21.7
	Irrigated	21.2^{b}	22.4^{a}	22.7^{a}	22.1
	Average	20.8	22.0	22.9	21.9

In each trait, different letters indicate significant differences at .05 level among fertilization treatments within certain irrigation regime

In each trait, different numbers indicate significant differences at .05 level between irrigation regimes within certain fertilization treatment

0P: 0 kg/ha P fertilizer, 45P: 45 kg/ha P fertilizer, 90P: 90 kg/ha P fertilizer

Table 6. The effect of drought stress on pod number (/plant), yield (t/ha), protein concentration (%) and oil concentration (%) of soybean cv. Boglár under different P-fertilizer rates

Trait	Irrigation regime	0P	45P	90P	Average
Pod number	Drought-stressed	36.2^{b2}	39.9^{a}	40.3^{a}	38.8
	Irrigated	38.4^{1}	40.1	40.5	39.7
	Average	37.3	40.0	40.4	39.2
Yield	Drought-stressed	3.7^{b2}	4.4^{a2}	$4.4^{a}2$	4.2
	Irrigated	4.4^{b1}	5.0^{a1}	5.1^{a1}	4.8
	Average	4.1	4.7	4.7	4.5
Protein concentration	Drought-stressed	39.6^{1}	40.9^{1}	39.9^{1}	40.1
	Irrigated	34.3^{2}	34.5^{2}	34.2^{2}	34.3
	Average	36.9	37.7	37.1	37.2
Oil concentration	Drought-stressed	21.2^{c2}	22.6^{b2}	23.7^{a2}	22.5
	Irrigated	23.0^{b1}	24.3^{a1}	24.9^{a1}	24.1
	Average	22.1	23.4	24.3	23.3

In each trait, different letters indicate significant differences at .05 level among fertilization treatments within certain irrigation regime

In each trait, different numbers indicate significant differences at .05 level between irrigation regimes within certain fertilization treatment

0P: 0 kg/ha P fertilizer, 45P: 45 kg/ha P fertilizer, 90P: 90 kg/ha P fertilizer

90P treatment, on the other hand, resulted in higher protein concentration only under drought stress conditions, but not under irrigated conditions. However, all differences were insignificant (tables 5 and 6).

Drought stress resulted in significantly higher protein concentration in both cultivars, regardless of fertilization treatment. The average protein concentration was 4.8 and 16.9% higher of drought-stressed Pannonia Kincse and Boglár plants, respectively compared to their irrigated counterparts (tables 5 and 6). 31.2% of increased protein concentrations were attributed to drought stress in Pannonia Kincse, and drought had even higher (84.7%) attribution in the case of Boglár cultivar.

Oil Concentration

Fertilization had highly significant effect on the oil concentration in both cultivars, and irrigation had significant effect on this trait in Pannonia Kincse cultivar, and even highly significant effect in the case of Boglár cultivar.

Both fertilization treatments (45P and 90P) significantly increased oil concentration in both cultivars and under both irrigation regimes. Moreover, 90P treatment had significantly higher oil concentration than 45P treatment in both cultivars under drought stress conditions, but not under irrigated conditions. Compared to 0P treatment, 45P and 90P treatments resulted, on average, in 5.8 and 10.1% higher oil concentration, respectively in Pannonia Kincse, and 5.9 and 10.0%, respectively in Boglár (tables 5 and 6). Fertilization rates were responsible for 74.8 and 69.3% of differences in this trait in Pannonia Kincse and Boglár, respectively, with a highly significant correlation of this trait with fertilization treatments (tables 3 and 4).

Drought, on average, resulted in reducing the oil concentration in both cultivars, with more measurable effect in Boglár, where the difference was significant, regardless of fertilization treatment (with and average reduction of 6.6%) (tables 5 and 6). Similar to its effect on the protein concentration, drought affected Boglár cultivar by a higher ratio (62.2%) than did on Pannonia Kincse cultivar (13.6), which is further supported by the correlation coefficient, as it was highly significant in Boglár, but not in Pannonia Kincse (tables 3 and 4).

DISCUSSION

Results of this study showed that P-fertilizer application increased LAI in both cultivars under both irrigation regimes. He et al. (2019) experimented 2 soybean genotypes different in yield and water use; Huandsedadou (HD) and Zhonghuang 30 (ZH). They imposed both genotypes, 15 days after sowing, to cyclic water stress by withholding irrigation until soil water capacity reached 30% of pot capacity and then re-watered the plants again, whereas control plants were kept under 85-100% pot capacity. Each water treatment received either 60 or 120 kg/ha of P fertilizer. Their results showed that P enhanced LAI at both flowering and maturity stages. Averaged over the two genotypes, 60P, under drought stress conditions, increased LAI by 100 and 43% at flowering and maturity, respectively. 120P increased this trait by 113 and 48% at flowering and maturity, respectively. Under well-watered conditions, 138 and 46% increases in LAI at flowering and maturity, respectively were recorded in 60P, and 192 and 49% in 120P, respectively. The authors also reported that drought stress decreased LAI at both flowering (by 48%) and maturity (by 47%), which supports the results of this study, as drought stress reduced LAI in both cultivars.

Plant height in both cultivars was significantly enhanced by P application; however, 90P did not measurably affect this trait compared to 45P counterpart. Adjei-Nsiah et al. (2019) tested the effect of 2 different sources of P fertilizer; triple superphosphate (TSP) (46% P2O5) and Morocco phosphate rock (MPR) (30% P2O5) on 3 soybean genotypes. Fertilization rate was applied at 30 kg P ha−1. They concluded that P fertilization from both sources significantly increased the plant height; by 10.5% in MPR treatment, and by 21.1% in TSP treatment. Significant decrease in plant height was caused by drought stress in both Pannonia Kincse and Boglár cultivars. An indeterminate soybean cultivar (OAC Bayfield) was put under two drought stress severities; W1 and W2 (corresponding to 25 and 50% of crop evapotranspiration (ETc), respectively as compared to control, 100% ETc) at R1 stage (Atti et al., 2004). Plant height decreased by 33 and 28% in W1 and W2 treatments, respectively after 9 days of stress application. Furthermore, after 16 days of drought imposition resulted in 56 and 47% reduction in plant height in W1 and W2 treatments, respectively. Gavili et al. (2019) reported a 33 and 60% plant height reduction in their experiment under 70 and 55% FC conditions, respectively compared to control counterparts. Drought reduced soybean plant height by 31.1% (Freitas et al., 2016). Neilson and Nelson (1998) explained this reduction in plant height under drought by the delayed stem elongation caused by shortened distance among nodes.

Based on the results of this study, P fertilization increased pod number/plant in both cultivars, however, its effect was more measurable on Boglár cultivar. He et al. (2019) reported that pod number/plant increased (by 13 and 140% in HD and ZH, respectively) in 60P under drought, whereas 120P did not further increase this trait. They also reported that under well-watered treatment, pod number/plant increased by 74 and 89% in 60P for HD and ZH, respectively, whereas 120P further increased this trait for HD, but not for ZH. Kamara et al. (2007) conducted field experiments to evaluate the response of four soybean cultivars to P application (0, 20, and 40 kg P/ha). Their results demonstrated that pod number/plant increased by 42.5% when 20 kg/ha of P fertilizer was applied, whereas 40 kg/ha P increased this trait by 56.0%. Adjei-Nsiah et al. (2019) found out that both P-fertilizer sources did not enhance pod number/plant in the pot experiment, whereas 8.3 and 22.3% more pod/plant were recorded when P was applied from MRP and TSP sources, respectively. Moreover, they concluded that P-fertilizer from TSP source had significantly greater number of pods than both P-fertilizer treatment from MRP source and the non-fertilized control. Similar results were reported earlier by Rani (1999). In this experiment, pod number/plant was reduced by drought stress, with more recordable effect on Pannonia Kincse cultivar. It was previously reported that drought stress negatively affects pollination process, leading to increased flower and pod abortion (Desclaux et al., 2000; Fang et al., 2010). Pod number/plant decreased by 49 and 43% in HD and ZH, respectively as a result of drought stress application (He et al., 2019).

Results showed that protein concentration in both cultivars was enhanced by 45P treatment, whereas 90P resulted in higher protein concentration under drought stress conditions only. Jin et al. (2006) tested 2 soybean genotypes different in seed protein concentration; Heisheng 101 (a genotype with high Protein concentration in the seeds) and Dongnong 46 (a genotype with low protein concentration in the seeds). Their results demonstrated that regardless of water availability, in both genotypes both 15P and 30P increased seed protein compared to 0P, however, 15P was higher than 30P in most cases (Jin et al., 2006). Drought stress, in this experiment, significantly increased seed protein concentration in both cultivars. Increased protein contents under drought stress were reported earlier (e.g. Rotundo and Westgate, 2009; Wang and Frei, 2011) and were explained by drought stress rapidly remobilizing nitrogen from leaves to seeds (Brevedan and Egli, 2003) which leads to increasing protein concentration, or by reducing seed number with increased seed size (Borras et al., 2004).

Oil concentration in seeds depends on many factors including the crop, variety, weather conditions and fertilization of with different nutrients (Hřivna et al., 2002; Lošák et al., 2010). Based on the findings of the current study, oil concentration significantly increased in both cultivars as a result of P-fertilizer application. The results are consistent with those of Costache and Nica (1968) and Dadson and Acquaah (1984) who concluded that increasing P rate significantly increased oil concentration in the seeds. Also, Win et al. (2010) reported that adding 1.0 mmol/l of P (in the form of KH_2PO_4) to Hoagland solution (1 mM P) increased oil concentration in three soybean cultivars by 7.1%, whereas further increasing P concentration to 2 mM P reduced oil concentration by 3.3% compared to 1 mM P treatment, yet it was still higher that non-fertilized control by 3.6%. Drought stress reduced oil concentration in both cultivars. Results of many studies indicated that drought stress reduced oil concentration in soybean seeds (e.g. Bellaloui and Mengistu, 2008; Maleki et al., 2013).

In this experiment, significant increase in the final seed yield was recorded in P-fertilized treatments compared to non-fertilized counterpart, regardless of cultivar or irrigation treatment. 90P treatment, however, further increased the yield under non-stressed conditions only compared to 45P treatment. Soil available-P deficiency is an important limiting factor in the development and the final yield of soybean (Wissuwa 2003). In their experiment, Jin et al. (2006) reported that in Heisheng 101, 15P increased yield by 1.4% when there was no drought, and by 9.3 and 16.5% when drought occurred at R1 and R4, respectively. 30P increased yield by 12.1% compared to 15P under no-drought, but reduced it by 5.9 and 3.4% under drought at R1 and R4, respectively but still higher than 0P. In Dongnong 46, only 30P increased yield compared to 0P under no-drought, but both 15P and 30P increased yield by 1.1 and 5.0% when drought happened at R1, and by 52.1 and 68.9% when drought happened at R4 (Jin et al., 2006). The authors also reported that seed yield was significantly associated with P accumulation before and after the initial pod filling (R5) stage and also with the total P accumulation. Zheng et al. (2009) studied an area consisting of 43 soybean fields in China in 2007 when soybean plants suffered from severe drought stress. The authors reported that P-fertilizer rate was the highest effecting factor (by 60.6%) that was attributed to differences in the final yield. Adjei-Nsiah et al. (2019) reported that yield was enhanced by P fertilization from both sources (by 10.0 and 8.6% in MPR and TSP treatments, respectively); however, the increases were insignificant. 52 and 63% higher seed yields were recorded in 20P and 40P treatments, respectively compared to 0P counterpart (Kamara et al., 2007). The authors reported that seed yield was strongly associated with pod number/plant and seed weight. Similar conclusions on yield enhancement by P application was also reported by Lamptey et al. (2014) and Ronner et al. (2016). The application of P fertilizer in the recommended rate (35 kg/ha) significantly increased the yield by 71% (Mahanta et al., 2014). Under drought stress conditions, the yield increased by 10 and 50% in 60P, and by 30 and 63% in 120P for HD and ZH, respectively. Under well-watered conditions, however, 60P increased the yield by 143 and 41% for HD and ZH, respectively, whereas 120P did not have measurable effect on the final yield (He et al., 2019). The authors attributed the yield improvement by P application to the improved filled-pod number and grain number, whereas B´elanger et al. (2002) concluded that P application enhanced the shoot biomass and, consequently, the seed yield. Drought stress significantly reduced the final seed yield in both cultivars and under all fertilization treatments. Similar conclusion was reported by Jin et al. (2006) who also reported that the application of P fertilizer could mitigate the negative effect of drought stress on yield in both cultivars. Other researchers reported similar effect in soybean (He et al., 2017a) and in other crops [moth bean (Garg et al., 2004) and malting barley (Jones et al., 2003)]. Drought stress decreased the yield of both genotypes (by 60 and 50% in HD and ZH, respectively) (He et al., 2019). Many previous papers reported similar negative effect of drought stress on soybean seed yield (e.g. Manavalan et al., 2009; Masoumi et al., 2011; Behtari and Abadiyyan, 2009; He et al., 2017b).

CONCLUSIONS

The physio-morphology of soybean is measurably affected by both P fertilization and drought stress, with more significant effects on stomatal conductance and plant height traits. In addition, pod number/plant and, consequently, the final seed yield were noticeably affected by the application of P fertilizer, however, the high rate (90P) did not significantly increase these traits compared to the lower rate (45P). Drought, on the other hand, significantly decreased both traits. P application significantly increased the oil concentration in the produced seeds, with more significant effect under drought stress conditions, whereas it did not affect the protein concentration trait. Drought stress, on the other hand, significantly increased protein concentration, but reduced oil concentration in the produced seeds.

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