Providing nutritional sources is crucial in order for plants to achieve optimum yield and quality of the produced yield; this becomes more important under stress conditions, to which drought belongs, representing one of the mainly increasing abiotic stresses. P fertilizer has a special role in enhancing the rooting system of plants, which might help in overcoming negative drought influence by enhancing water and nutrient uptake. Soybean is classified as a drought-sensitive legume, providing cheap source of both protein and oil. To evaluate the influence of P fertilizer on soybean yield and quality under moderate drought, an experiment was conducted in 2018 by applying three P fertilizer rates (0, 45 and 90 kg ha$^{-1}$ of P$_2$O$_5$) to soybean (cv. Boglár) under two irrigation regimes; irrigated and moderate-drought-stressed regimes. Results showed that drought had negative effects on both yield and oil concentration; however, P application could alleviate drought's effects by enhancing both traits, moreover, it could enhance these traits when drought was waived off as well. P application had very small effect on protein concentration which was significantly higher under moderate drought conditions. Applying relatively-high rate of P could further increase oil concentration compared to lower P rate, however, it did not enhance yield or protein concentration. It was concluded that applying P fertilizer has positive effects on both yield and seed quality of soybean, especially under moderate drought, however, higher rate of P fertilizer had little influence on oil concentration only.

KEY WORDS: drought stress; irrigation regimes; P fertilizer; seed quality; soybean; yield

Introduction

Soybean (Glycine max (L.) Merrill) is among the most grown crops worldwide (He et al., 2017), and the most widely grown seed legume that provides an inexpensive source of protein (Hao et al., 2013), in addition to being the most widely grown oilseed crop (Cerezini et al., 2016).

One of the major abiotic stresses affecting soybean plants is drought stress (Fan et al., 2013) as soybean is widely sown under rain fed conditions that are noticeably influenced by the current global climatic changes. Soybean is highly sensitive to drought, especially during the reproductive stages (Sinclair and Serraj, 1995; Brevedan and Egli, 2003; Oya et al., 2004). At this period, drought stress reduces pod number and accelerates leaf senescence, shortens seed-filling period and results in smaller and lighter seeds (Fredrick et al., 2001; Egli and Bruening, 2004; Liu et al., 2004; Manavalan et al., 2009). The annual soybean yield reductions caused by drought are enormous (Sinclair et al., 2007; Sincik et al., 2008), reaching up to 40% (Manavalan et al., 2009). Under drought stress conditions, P can enhance vegetative development, net photosynthetic rate, carbohydrate metabolism, root morphology and P uptake which, in part, positively affects seed number and size and, consequently, seed yield (Gutierrez-Boem and Thomas, 1999; Garg et al., 2004; Jin et al., 2006).

Phosphorus (P) is one of the most important limiting nutrients in plant growth and production (Elser et al., 2007); it plays an important role in chloroplast composition and in photosynthesis (Hernández and Munné-Bosch, 2015). Soybean is a Phosphorus-dependent crop, and proper applied rates of phosphorus improve physiological characteristics and enhance nutrient uptake and production (Yan et al., 1995); consequently, deficiency in available phosphorus in the soil results in limitations in soybean development and final yield (Suman and Singh, 1985; Wissuwa, 2003).

It was previously reported that phosphorus application enhanced mean plant height (Dadson and Acquaah, 1984), photosynthesis (Robson et al., 1981), node number per plant and pod number per plant (Dadson and Acquaah, 1984), dry matter accumulation (Hu et al., 2002; Dong, 2009), biomass and P uptake (Goswami et al., 1999; Andraski and Bundy, 2003) and yield (Hu et al., 2002; Dong, 2009). The positive role of P in plant's growth and development was differently justified; Xue et al. (2014) concluded that suitable P concentrations
resulted in distributing dry matter more effectively in the pods of the soybean plants, which resulted in yield enhancement, whereas Ankomah et al. (1996) reported that the positive effect of added P on cowpea grain yield was most probably due to its role in increasing nodules mass and consequently the amount of fixed N₂; this was confirmed by the findings of Al-Chammaa et al. (2014) who reported quantities of N derived from atmosphere through fixation process to increase from 30.3 kg N ha⁻¹ when P fertilizer was not applied to 35.6 and 37.2 kg N ha⁻¹ when 40 and 80 kg ha⁻¹ P, respectively, were applied to soybean plants. Also for beans, P fertilizer resulted in consistent responses in grain yield (Hungria et al., 2000).

Furthermore, Zheng et al. (2009) concluded that enhanced rates of P in the fields with lower soybean yields were the most practice needed for increasing soybean yield. Applying P fertilizer to soybean in a soybean-maize rotation cropping system lead to high biomass and grain yield of soybean, and also to better performance of the subsequent maize crop (Kihara et al., 2010; Vandamme et al., 2014). However, excessive P rates negatively-affected soybean development (Cai et al., 2004). Zheng et al. (2009) concluded that applying P fertilizer under drought stress conditions can alleviate yield reduction resulted from N₂ fixation decline as P stimulates biological N₂ fixation and increases N accumulation in seeds (Graham and Vance, 2000; Ogoke et al., 2003). Zheng et al. (2015) investigated the different factors that affects soybean yield variability in Hailun County, China; the number of the analyzed fields was 101 in 2009 and 109 in 2010; they reported that available P in the soil was the most important soil variable controlling yield variations in both years. Although some controlled-chamber studies focused on P ability to alleviate soybean yield-loss under drought conditions (e.g. Gutierrez-Boem and Thomas, 1999; Jin et al., 2006), yet field experiments that investigated the combined effects of drought and phosphorus on soybean are scarce. The aim of our research was to investigate the influence of different phosphorus rates on both the yield and the seed quality of soybean (cv. Boglár) under irrigated and moderate drought-stressed regimes.

Material and methods

Soybean (cv. Boglár) was sown in Debrecen University's experimental site (Látókép) (N. latitude 47°33’, E. longitude 21°27’) on April 23rd and was harvested on September 20th, 2018. The soil type is calcareous chernozem, the 10-year-average annual precipitation (2001–2010) is 520.7 mm, whereas the precipitation between sowing and harvesting dates was 266.8 mm (Fig. 1).

Three P fertilizer rates; 0, 45 and 90 kg ha⁻¹ P₂O₅ (0P, 45P and 90P, respectively) were applied under two irrigation regimes; moderate drought stress regime (accounting only on the precipitation as the only source of water supply) and irrigated regime (where an additional 50 mm of irrigation water was applied during full pod (R4) stage (Fehr and Caviness, 1977). Each treatment consisted of three replications. The statistical analysis was made using SPSS (ver.25) software.

Results and discussion

The precipitation during the months of May and June, which were adequate to the vegetative stages V1 to V6 besides the blooming stages R1 and R2, was very close to the monthly average; however, a noticeable reduction (by 47.1%) in the precipitation amount happened during July where the plants were at full pod R4 stage (particularly between 8th and 15th, where only 4.8 mm of precipitation was recorded, so an additional 50 mm of irrigation water was provided to the irrigated plots on July 9th so the total water amount received was adequate to the monthly average).

On the other hand, August recorded higher precipitation amount than average (Fig. 1); plants, however, were at the beginning of full maturity stage (R7) by that time.

| May | June | July | August |
|-----|------|------|--------|
| 69.2 | 66.8 | 61.9 | 51.5 |

Fig. 1. Water amounts [mm] of both irrigation regimes in 2018 as compared to the average precipitation [mm] during (2001–2010) in Debrecen, Hungary.
Yield [t ha\(^{-1}\)]

Under drought stress, (45P) treatment resulted in significantly higher yield (4.47 t ha\(^{-1}\)) compared to (0P) (3.80 t ha\(^{-1}\)) treatment, however, increasing P rate to 90 kg ha\(^{-1}\) (90P) did not result in noticeable yield enhancement (4.50 t ha\(^{-1}\)) (Table 1). These results can lead to a conclusion that applying P fertilizer could alleviate the negative effect of drought stress on the yield.

Under irrigated regime, applying P fertilizer resulted in relatively better yield (5.13 and 5.23 t ha\(^{-1}\)) for 45P and 90P treatments, respectively compared to control (4.60 t ha\(^{-1}\)), however, the differences were insignificant (Table 1). Previously, Li et al. (2001) reported that the application of P fertilizer (in a rate of 33 kg ha\(^{-1}\)) resulted in an increase in soybean’s seed yield by 6.7%. Similar conclusion was reported earlier (Dadson and Acquaah, 1984; Seneviratne et al., 2000). Al-Chammas et al. (2014) recorded an increase by 7% and 12% in seed yield when P fertilizer was applied at rates of 40 and 80 kg ha\(^{-1}\), respectively relative to control treatments (without P). Moreover, Aulakh et al. (2003) reported significant increases in seed yield as a result to direct application of P to soybean at rates up to 80 kg ha\(^{-1}\) (reaching 2.56 t ha\(^{-1}\)); however, higher rate of P (100 kg ha\(^{-1}\)) did not increase grain yield (2.53 t ha\(^{-1}\)). Similar conclusions were also reported (Dong, 2000; Ogoke et al., 2003; Wang et al., 2006). In general, the high rates of P fertilizers do not always effectively-improve crop yield, as crops readily use only 10–45% of applied P (Adesemoye and Kloeper, 2009). In soybean, high P rates decrease nitrogen and protein accumulation in the seeds (Zheng et al., 2015), which is relatively demonstrated by our results on protein concentration under high P rate (Table 1), as N accumulation plays a key role in protein concentration in the seeds as reported by many papers (e.g. Rotundo and Westgate, 2009). Yield was significantly (<0.05), positively correlated with P rate (Table 2).

The effect of drought was obvious when no P fertilizer was applied (0P); the drought-stressed treatment resulted in significantly less yield (3.80 t ha\(^{-1}\) relative to 4.60 t ha\(^{-1}\) under irrigated regime). On the other hand, the irrigated plots which received P fertilizer were better than the drought-stressed counterparts, though the increases were insignificant (Table 1). This comparison demonstrates the negative effect of drought stress on soybean yield, with an additional evidence of the ability of P fertilizer to reduce the negative influence caused by drought stress on soybean yield.

Many papers reported drought stress (regardless of its severity) to reduce soybean yield (e.g. Sadeghipour and Abbasi, 2012; Li et al., 2013; He et al., 2017). Also, it was previously reported that under drought stress conditions, the fields that received P fertilizer achieved greater yield than those that did not receive P fertilizer. Similarly, many papers reported that applying P fertilizer can enhance drought tolerance in soybean (Gutierrez-Boem and Thomas, 1999; Jin et al., 2006).

Under severe drought stress in 2007 in China, applied P rate to a study area of 43 fields was the most important factor in determining yield; applying lower P rate resulted in an average yield of 2.13 t ha\(^{-1}\), whereas higher P rate increased the average yield to 2.65 t ha\(^{-1}\); it accounted for 60.6% of the total variation in yield (Zheng et al., 2009). Yield was significantly (<0.05), positively correlated with irrigation regime (Table 3).

Table 1. The effect of different P fertilizer rates on yield [t ha\(^{-1}\)], protein concentration [%] and oil concentration [%] of soybean (cv. Bolgár) under two irrigation regimes

| Trait                | Moderate Drought Stress Regime | Irrigated Regime |
|----------------------|--------------------------------|------------------|
|                      | 0P  | 45P  | 90P  | 0P  | 45P  | 90P  |
| Yield [t ha\(^{-1}\)]| 3.80\(^2\) | 4.47\(^1\) | 4.50\(^1\) | 4.60\(^1\) | 5.13\(^1\) | 5.23\(^1\) |
| Protein Concentration [%] | 39.7\(^1\) | 40.6\(^1\) | 40.3\(^1\) | 33.6\(^1\) | 34.0\(^2\) | 33.6\(^2\) |
| Oil Concentration [%]  | 21.8\(^2\) | 22.8\(^2\) | 24.2\(^1\) | 23.5\(^1\) | 24.8\(^2\) | 25.2\(^1\) |

- Same letter indicates no significant difference at .05 level among P rates within certain irrigation regime.
- Same number indicates no significant difference at .05 level between the two irrigation regimes within certain P rate.

Table 2. Correlation of P fertilizer treatment with yield, protein concentration and oil concentration under irrigated and moderate drought-stressed regimes

| Trait                | Moderate Drought Stress Regime | Irrigated Regime |
|----------------------|--------------------------------|------------------|
| Yield [t ha\(^{-1}\)]| .788\(^*\) | .724\(^*\) |
| Protein Concentration [%] | .161\(^*\) | .009 |
| Oil Concentration [%]  | .853\(^**\) | .923\(^**\) |

- \(^*\). Correlation is significant at the 0.05 level (2-tailed).
- \(^**\). Correlation is significant at the 0.01 level (2-tailed).
Under both irrigation regimes, protein concentration was insignificantly enhanced in (45P) treatments, whereas (90P) treatments resulted in a very slight decrease (compared to 45P treatments) (yet they were better than 0P treatments) (Table 1). Dadson and Acquaah (1984) concluded that P application has lead, in general, to increased protein concentration in the seeds. Idris (1987) reported increased N accumulation in Lucerne (Medicago sativum L.) plants as a response to P application, which, in part, will lead to increased protein concentrations. The correlation with P rate was very small and insignificant (Table 2). The effect of drought was more obvious; the drought-stressed plots resulted in better protein concentration relative to irrigated counterparts. Moreover, the increase was significant when P was applied (regardless of rate), whereas it was noticeable, yet not significant, when P was not applied (Table 1). These results suggest that drought has a major positive effect on protein concentration. Increased protein concentration under drought stress compared to well-irrigated counterpart was previously reported in many papers (e.g. Bellaloui and Mengistu, 2008; Rotundo and Westgate, 2009; Wang and Frei, 2011). This increase was explained in some reports as a result to a reduction in seed number associated with an increase in seed size (Borras et al., 2004), whereas other papers concluded it to be caused by drought stress rapidly remobilizing nitrogen from leaves to seeds (Brevedan and Egli, 2003) which leads to enhanced protein concentration. The correlation with irrigation regime was significantly negative under all P rates (Table 3). Regardless of P application or rate, the decrease of yield, caused by drought stress, was accompanied by an increase in protein concentration (Table 1). Previously, Liang et al. (2010) reported that high protein concentration is negatively correlated with the yield in most cases; same conclusion was demonstrated later (Miransari, 2016).

### Protein Concentration [%]

Under both irrigation regimes, protein concentration was insignificantly enhanced in (45P) treatments, whereas (90P) treatments resulted in a very slight decrease (compared to 45P treatments) (yet they were better than 0P treatments) (Table 1). Dadson and Acquaah (1984) concluded that P application has lead, in general, to increased protein concentration in the seeds. Idris (1987) reported increased N accumulation in Lucerne (Medicago sativum L.) plants as a response to P application, which, in part, will lead to increased protein concentrations. The correlation with P rate was very small and insignificant (Table 2). The effect of drought was more obvious; the drought-stressed plots resulted in better protein concentration relative to irrigated counterparts. Moreover, the increase was significant when P was applied (regardless of rate), whereas it was noticeable, yet not significant, when P was not applied (Table 1). These results suggest that drought has a major positive effect on protein concentration. Increased protein concentration under drought stress compared to well-irrigated counterpart was previously reported in many papers (e.g. Bellaloui and Mengistu, 2008; Rotundo and Westgate, 2009; Wang and Frei, 2011). This increase was explained in some reports as a result to a reduction in seed number associated with an increase in seed size (Borras et al., 2004), whereas other papers concluded it to be caused by drought stress rapidly remobilizing nitrogen from leaves to seeds (Brevedan and Egli, 2003) which leads to enhanced protein concentration. The correlation with irrigation regime was significantly negative under all P rates (Table 3). Regardless of P application or rate, the decrease of yield, caused by drought stress, was accompanied by an increase in protein concentration (Table 1). Previously, Liang et al. (2010) reported that high protein concentration is negatively correlated with the yield in most cases; same conclusion was demonstrated later (Miransari, 2016).

### Oil Concentration [%]

Under both irrigation regimes, applying P fertilizer noticeably enhanced oil concentration in the seeds; more particularly, (45P) treatment resulted in better oil concentration relative to (0P) treatment, and further increase of P rate (90P) resulted in further increase in oil concentration, and though this increase was insignificant relative to the (45P) treatment, yet it was significantly better as compared to the (0P) counterpart treatments (Table 1). Our 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. The correlation with P rate was highly significant (<0.01) (Table 2). The effect of drought on oil concentration was also measurable regardless of P application and rate; irrigation significantly increased oil concentration for both (0P) and (45P) treatments, whereas the increase was insignificant when applying higher P rate (90P) (Table 1). Results of many studies indicated that drought stress reduced oil concentration in soybean seeds (e.g. Bellaloui and Mengistu, 2008; Maleki et al., 2013). Oil concentration correlation with irrigation regime was highly significant (< 0.01) under (0P) and (45P) rates and insignificantly positive under (90P) rate (Table 3). Our results showed a negative relationship between oil and protein concentrations; the increase in oil concentration was accompanied by a reduction in protein concentration (Table 1). Chung et al. (2003) and Miransari (2016) reported similar conclusion.

### Conclusion

Drought stress had noticeable effects on soybean; it resulted in reducing the yield to distinctive levels; however, it increased protein concentration and slightly decreased oil concentration. P fertilization had positive effects on both yield and seed quality of soybean; its influence was more obvious on the yield and the oil concentration. Moreover, P fertilization was extremely important and useful under drought stress conditions as it could alleviate the negative effects on the yield. However, high rate of P fertilizer did not lead to significant increases in soybean's yield and seed quality as compared to moderate rate. An extension of this research to involve different drought stress severities during different stages of soybean's vegetative period will provide more accurate data and more understanding of the different reactions of soybean plants to P under drought stress conditions. In addition, involving both physiological and production traits will provide even more integrated data on how drought stress affects soybean's development and final yield and seed quality.
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Soybean yield and seed quality under moderate drought stress as affected by...

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