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Physiological Plant Response Differences among High- and Average-Yield Soybean Areas in Arkansas

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Abstract

Increasing soybean [*Glycine max* (L.) Merr.] yields requires a multi-pronged approach. Annual state soybean yield contest fields can provide information about yield potentials and plant response differences between high and average-yield producing areas. The objectives of this study were to i) assess plant physiological property and elemental seed concentration differences between high- (HY) and average-yield (AY) areas and across soybean growth stages and ii) evaluate relationships among plant properties and yield across the seven regions of the "Grow for the Green" soybean yield contest in Arkansas. Seed yields in AY and HY areas averaged 74.4 and 88.3 bu/ac, respectively, in 2015. Harvest index, average seed weight, and seed K concentration differed ($p < 0.05$) by at least 10% across growth stages and between yield areas. Averaged across growth stage, aboveground dry matter and seed B and C concentrations differed ($p < 0.05$) by at least 0.7% between yield areas across regions. Averaged across yield area, seed N, P, Ca, Fe, Mn, Zn, Cu, and B concentrations differed ($p < 0.05$) by at least 2.5% across growth stages. Planting date was most strongly correlated with yield ($p < 0.001$; $r = -0.62$), confirming previous research. Encompassing a wide variety of landscapes and management systems, results of this study validate the importance of planting date to soybean yield. Additional factors need to be evaluated to discover stronger relationships with yield to continue closing the soybean yield gap.

From 1924 to 2012, the average United States soybean [*Glycine max* (L.) Merr.] yield increased by 0.4 bu/ac/yr, from 12 to 42.4 bu/ac (Egli, 2008; Van Roekel and Purcell, 2014). However, soybean yields greater than 100 bu/ac have been reported in soybean yield contests in multiple states since 2014. Research focusing on managing soybean for high-yield production has concentrated on maximizing light interception and crop growth rate before the mid-R5 reproductive stage (Fehr et al., 1971) to provide the maximum level of photosynthate for translocation to seeds (Westgate, 2001). Although choosing the correct row spacing, plant population, variety, and planting day of year and maximizing light interception before R5 contributes to achieving the greatest amount of photosynthate, perhaps resulting in the largest-producing combination is dependent on achieving the greatest efficiency for seed formation and resulting final yield (Westgate, 2001).

Core Ideas

- Crop yield contests provide a unique research opportunity.
- Planting date is highly related to yield across yield contest sites.
- An early soybean production system is advantageous for high yields.

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Abbreviations: ADM: Above-ground dry matter; ANOVA: Analysis of variance; ASW: Average seed weight; AY: Average-yield; DMAC: Dry matter allocation coefficient; EFP: Effective filling period; HI: Harvest index; HM: Harvest maturity; HY: High-yield; ICAP: Inductively coupled, argon-plasma spectrometry; PDOY: Planting day of year; SGR: Seed growth rate.

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Yield is determined by the final seed number (i.e., seed/m^2) and the final average seed weight (ASW), and of the two, seed number has the greatest impact on final soybean yield (Borrás et al., 2004; De Bruin and Pedersen, 2008; Van Roekel et al., 2015). Seed number is a function of the plants per unit area, pods per plant, and seeds per pod, which are determined by genetics and planting practices (Egli, 1998). As such, it becomes difficult to focus on just one component of seed number, and it is better to think of seed number instead as the total number of seeds or pods per unit area. Physiologically, a soybean crop will adjust its yield potential to match the available growing conditions. Thus, seed number (per acre) determination can be viewed as the crop setting the number of seeds the plants can support (Westgate, 2001). Previous studies have shown seed number determination is closely related to photosynthate production from R1 to R5 (Andrade and Ferreiro, 1996; Mathew et al., 2000; Sharma et al., 1990; Van Roekel et al., 2015). The following seed-fill period from R6 to R7 will have a major impact on final seed weight, which will also influence yield. This understanding of how yield is determined in soybeans is the crucial first step in making management decisions for sustainable yield increases over time.

Prior to flowering, abiotic and biotic stresses do not have a large impact on final yield, provided that the stress did not severely stunt the plants (Egli, 1998). Therefore, maximizing yield depends on alleviating all stresses throughout the entirety of reproductive development. Both excess available water and insufficient water can have a large impact on photosynthesis and crop growth, while soil fertility and pH must also allow for optimal crop growth rates (UACES, 2014). Soil fertility and pH, as well as irrigation practices, should be managed according to soil and plant analyses in conjunction with the yield goal and calculated crop demands (UACES, 2014). In recent decades, soybean yield goals have been pushed through producer experimentation to place highly in sponsored yield contests.

Yield-contest data provide useful information regarding achieving maximum crop yields. In 1966, the first soybean yield contest in the US was held nationwide when two producers achieved yields of 98.9 bu/ac in Chenoa, IL and Hamburg, IA (Cooper, 2003). Yields of greater than 100 bu/ac were recorded during the 1968 National Yield Soybean Contest, when 110 and 117 bu/ac were harvested in Rolling Prairie, IN and Ozark, MO, respectively (Cooper, 2003). Nationwide, yield contests are currently conducted in 14 states, including Arkansas (Van Roekel and Purcell, 2014), with the 100 bu/ac yield mark the target goal for producers across the country.

In 2015, Arkansas ranked eleventh in planted soybean area nationwide and achieved the eight-greatest mean yield by state (52.5 bu/ac; USDA-NASS, 2016). Arkansas soybean production is primarily concentrated in the Southern Mississippi Alluvial Valley, where Mississippi County surpassed all other counties in planted and harvested area in 2014, but Desha County led Arkansas in productivity with a mean yield of 66.5 bu/ac (USDA-NASS, 2016). The first year of the soybean yield contest in Arkansas, "Grow for the Green", was 1999, when the greatest mean yield was 82.2 bu/ac (ASA, 2015a). In 2007, the "Race for 100" soybean yield contest was established in Arkansas as a way of promoting the goal of producing 100 bu/ac (ASA, 2015b). The 100 bu/ac yield barrier was broken in 2013, when three producers in Arkansas had yields of 108, 112, and 115 bu/ac (ASA, 2015a).

Evaluating producers' fields that produce high soybean yields in Arkansas may provide relevant information for other producers who are striving to achieve soybean yields equal to or greater than a recent world record yield (171 bu/ac), which was harvested in Georgia in 2016 (Haire, 2016). Additionally, through characterization of plant physiological properties and mechanism differences that occur in contest- and high-yield management areas as well as in average-yield areas in the same or adjacent fields, consistencies and patterns in soybean physiology may be observed that explain large yields occurring under various management practices. Therefore, the primary objective of this study was to evaluate plant-property and seed-chemical-concentration differences between high- and average-yield areas and across late soybean growth stages [mid-R5, mid-R6, and R8 or harvest maturity (HM)] to determine which properties are most related to ultra-high soybean yields. The secondary objective of this study was to identify correlations among these measured variables and soybean seed yield.

"Grow for the Green" Yield Contest

An annual soybean yield contest, "Grow for the Green", was initiated by the Arkansas Soybean Promotion Board (ASPB) and the Arkansas Soybean Association (ASA) in 1999. In 2011, the ASPB and ASA divided the contest entries into three production systems: early season, full-season, and double-crop. In 2013, Arkansas was split into seven geographic regions (Fig. 1), and an eighth, statewide, non-genetically-modified-organism contest category. The seven geographic regions for the yield contest are: 1- Northeast Delta, 2- Northeast, 3- White River Basin, 4- Central and Grand Prairie, 5- East Central Delta, 6- Southeast Delta, 7- Western (Fig. 1).

Study Area Descriptions

In late spring to early summer 2015, one producer in each of the seven regions was identified as a willing cooperator who had a field area entered into the 2015 yield contest, as well as an average-yielding area within the same field or in an adjacent field in the same soil mapping unit. The average-yielding area identified was based on each producer's qualitative, historic knowledge of the productivity of their own fields and areas within fields.

Soybean varieties planted were the same in HY and AY areas within Regions 1, 2, and 4 (Table 1), but the variety planted differed slightly between AY and HY areas in the other four regions (i.e., Regions 3, 5, 6, and 7). However, for all regions, the variety planted in the HY and AY areas within a region were in the same maturity group (Table 1), thus suggesting

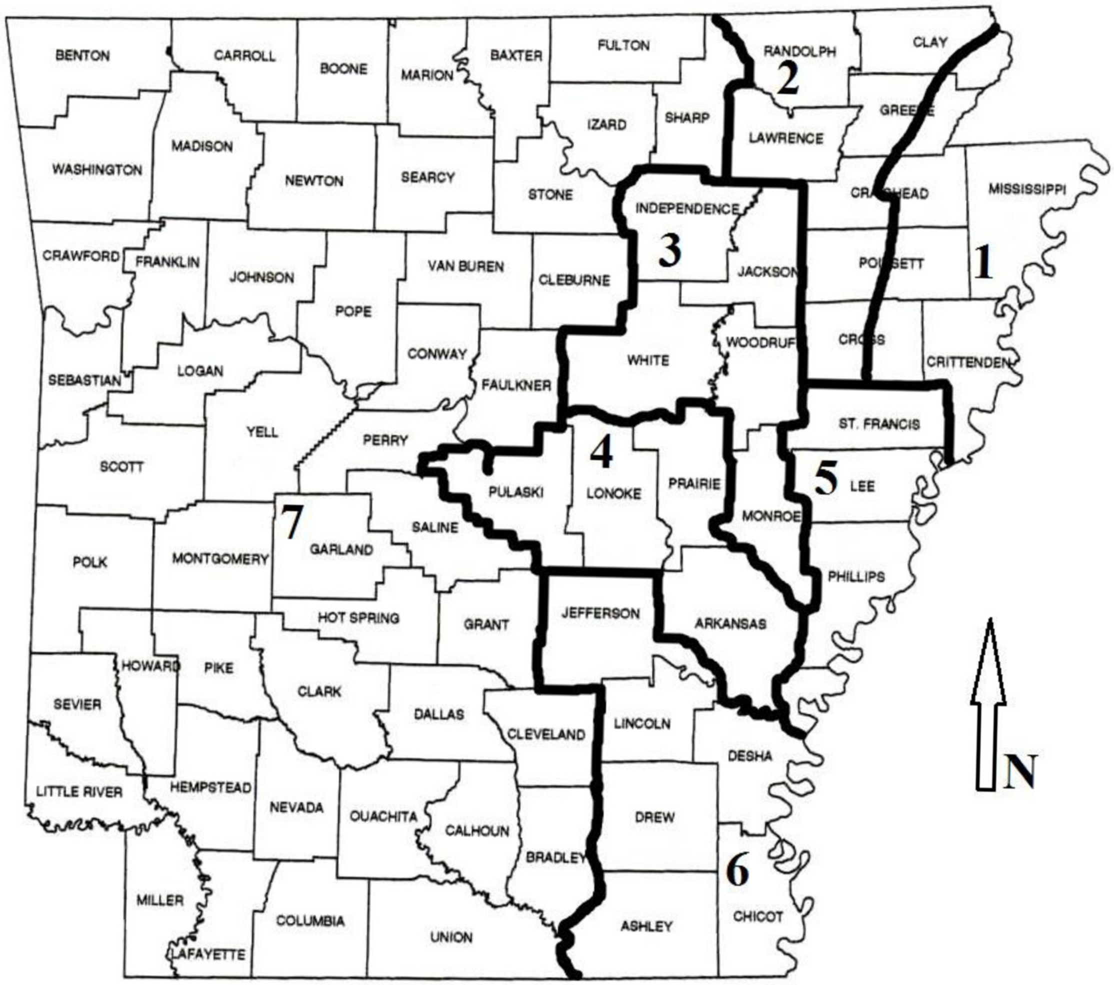

Fig. 1. The "Grow for the Green" soybean yield contest, sponsored by the Arkansas Soybean Promotion Board and the Arkansas Soybean Association, divides Arkansas into seven regions: 1- Northeast Delta; 2- Northeast; 3- White River Basin; 4- Central and Grand Prairie; 5- East Central Delta; 6- Southeast Delta; and 7- Western.

Table 1. Variety planted, planting day of year (PDOY), and final yield for high-(HY) and average-yield (AY) areas for the fields sampled in the seven regions in the "Grow for the Green" yield contest across Arkansas in 2015. Variety, PDOY, and yield from average-yield areas were reported by growers while yields from high-yield areas were reported by growers or verified by ASA (2015a). Values are rounded.

Region	HY			AY		
	Variety	PDOY	Yield (bu/ac)	Variety	PDOY	Yield (bu/ac)
1	Asgrow 4633	107	96.8	Asgrow 4633	100	59.4
2	USG 74E88	166	73.4	USG 74E88	166	64.2
3	Asgrow 4632	121	116.8	Pioneer 46T21	120	94.3
4	Pioneer 47T36	157	83.6	Pioneer 47T36	156	76.1
5	Asgrow 4835	98	85.7	Asgrow 4632	98	78.8
6	Pioneer 47T36	98	116.8	Pioneer 45T11	96	105.0
7	Rev 49R94	156	45.0	Pioneer 94Y70	155	42.9

similar, but not identical, yield potentials and indicating some level of comparability despite not being the exact same variety. Similar to variety, planting day of year in HY and AY areas was the same in some regions, but not in others. However, planting day did not differ between yield areas by more than 7 d in any region (Table 1) and the AY areas were always planted before the HY areas. Irrigation management, row spacing, and seeding density were similar between yield areas within all regions (data not shown).

Among producer fields included in this study, the soil parent material was mostly alluvium, except for in Regions 3 and 5, which were eolian and loess, respectively (Adams, 2016). Soil surface textures were silt loam in all regions except for Region 3, which was fine sandy loam (Adams, 2016). All soils in producer fields were Alfisols, except for in Region 3, which was an Inceptisol (Adams, 2016).

Annual precipitation varied slightly across the seven regions (Table 2), with annual precipitation in counties sampled ranging from 48.2 inches in Craighead and Cross Counties in the northern portion of Arkansas (Regions 1 and 2; Fig. 1) to 53.7 inches in Desha County, in the southern part of the state (Region 6). As with precipitation, average monthly air temperatures varied across the state, but only slightly (Table 2). The lowest average January air temperature (35.8°F), as well as the lowest average annual air temperature (59.2°F), both occurred in Craighead County (Table 2). Similar to the low air temperatures, the largest average July air temperature of counties sampled (82.6°F) occurred in Philips and Desha Counties, and the largest annual temperature (63.0°F) occurred in Desha County. Based on direct information obtained from the various cooperating landowners, there were no extreme temperature or precipitation events in 2015 to have substantially negatively affected crop growth or productivity at the sites that were sampled for this study.

Sample Collection and Processing

During the 2015 growing season, sample points were established in a five-point diamond formation within each HY and AY areas, which ranged in size from 5 to 7 ac (2 to 2.8 ha), in each of the contest regions. Three of the five points were in the same row approximately 203 ft apart from one another, and the other two points were perpendicular to the middle row approximately 125 ft in the opposite direction from the mid-point of the middle row. At each point, above-ground plant material was collected from five consecutive plants within a row at the mid-R5 and mid-R6 growth stages, as defined by Fehr et al. (1971), and also at HM. The mid-R5 samples were collected from the adjacent row immediately to the left of the row that was used for HM sample collection, while the mid-R6 samples were collected from the adjacent row immediately to the right. For all three growth stages, the total above-ground plant material was dried at ~ 130°F for 7 d, and weighed to determine above-ground dry matter (ADM), then seeds were removed, counted, weighed, and seed number (seeds/plant) was calculated. A subsample of the seed material was ground in a coffee grinder to pass a 0.04-in mesh sieve, and N and C concentrations were determined by high-temperature combustion using a VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ). For determination of elemental seed-tissue concentrations (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B), seeds were digested using concentrated HNO_3 and analyzed by inductively coupled, argon-plasma spectrometry (ICAP, Spectro Analytical Instruments, Spectro Arcos ICP, Kleve, Germany).

For processing of soybean seed from the mid-R5 and mid-R6 sample dates, pods were removed from stems and were vigorously and manually shaken in all directions in plastic jars with rubber stoppers until seeds were removed from pods. Seeds were then placed on a series of sieves (i.e., 0.2- and 0.1-in mesh screens for the mid-R5 seeds and 0.3-in and 0.1-in mesh screens for the mid-R6 seeds) to remove any pod material remaining from the samples. Samples were subsequently placed on trays and the smallest seeds (i.e., those that were still in the lag phase; Egli, 1998) were eliminated by lightly, orally blowing across the surface of the tray. This process effectively removed seed that was still in the lag phase of growth, before the linear period between the mid-R5 and mid-R6 growth stages.

Seed-weight increases from the mid-R5 to mid-R6 sample dates were used to determine the seed growth rate (SGR; mg/seed/d). The final ASW divided by the SGR was then used as an estimate of the duration of the effective seed-filling

Table 2. Climate and geographical data for the Arkansas counties represented in the 2015 plant sampling. Climate data were obtained from the SRCC (2015) and are 30-yr normal values.

Region	County	MLRA†	Annual precipitation (in)	Air temperature		
				July (°F)	January (°F)	Annual (°F)
1	Craighead	131A	48.2	80.2	35.8	59.2
2	Cross	131A, 134	48.2	80.4	37.6	60.1
3	Woodruff	131A	49.2	81.9	36.7	60.8
4	Lonoke	131B, 131D	48.6	81.1	41.4	62.4
5	Phillips	131A, 134	50.8	82.6	40.5	62.6
6	Desha	131B	53.7	82.6	42.4	63.0
7	Conway	118A	49.9	80.6	38.1	59.9

† Major Land Resource Area (MLRA): 118A- Arkansas Valley and Ridges, Eastern Part; 131A- Southern Mississippi River Alluvium; 131B-Arkansas River Alluvium; 131C– Red River Alluvium; 131D- Southern Mississippi River Terraces; 134– Southern Mississippi Valley Loess (USDA-NRCS-MLRA, 2014a).

period (EFP). Harvest index (HI), the weight proportion of the vegetative plant that was seed, was used to calculate the dry matter allocation coefficient (DMAC; Salado-Navarro et al., 1985), defined as the rate of increase in HI from the R5 to R6 sample dates. Similar to EFP, EFP2 was then calculated by dividing the HI at HM by the DMAC.

Data Analyses

A two-factor analysis of variance (ANOVA), assuming a completely random design, was conducted using SAS (version 9.3, SAS Inst. Inc., Cary, NC) to evaluate the effects of yield area (i.e., high- and average-yielding areas), growth stage (i.e., mid-R5, mid-R6, and HM), and their interactions on measured and calculated plant properties (i.e., ASW, HI, and seed N, C, P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B concentrations). In addition, a one-factor ANOVA was conducted using SAS to evaluate the effect of yield area on yield, SGR, EFP, DMAC, and EFP2. Since ADM and seed number (seed/plant) were used in calculations to determine HI and SGR, respectively, statistical analyses of ADM and seed number were not performed separately. Significance was judged at $p < 0.05$. When appropriate, means were separated by least significant difference at $\alpha = 0.05$.

Linear correlation analyses were conducted to evaluate the relationships among seed N concentrations, SGR, ASW, EFP, HI, DMAC, EFP2, and planting day of year and yield combined across both yield areas. All correlations were performed in JMP (version 12 Pro, SAS Inst. Inc., Cary, NC). For the purposes of these analyses, region was treated as a random variable, as there was no replication within a region. Therefore, results apply to combined data across all regions.

General Yield and Plant Property Variations

Soybean yields in the average-yield areas ranged from 42.9 bu/ac in Region 2 to 105 bu/ac in Region 6 (Table 1; Fig. 1). The mean yield for all average-yield areas was 74.4 bu/ac, which was 21.9 bu/ac greater than the Arkansas state average from 2015. Soybean yields in the HY areas of fields ranged from 45.0 bu/ac in Region 2 to 116.8 bu/ac in Regions 3 and 6, while the mean yield for all HY areas was 88.3 bu/ac (Table 1; Fig. 1). Regions 2, 3, and 6 of the yield contest are all in the eastern portion of Arkansas (Fig. 1); however, Region 2 has alluvial and loessial soils, while the soils in Region 3 were derived from a mix of alluvial and eolian parent materials (Table 1; USDA-NRCS, 2014b). Region 6 consists of terraces and lower-elevation alluvial sediments and is also further south, and has a slightly warmer climate (Table 2; USDA-NRCS, 2014b). In 2015, yield increases from each average- to the high-yield area within a field ranged from 5% in Region 2 to 63% in Region 1 (Table 1), where both of these regions had the same soybean variety planted in both the HY and AY areas. Despite some minor differences in varieties planted in the HY and AY areas in four of the seven regions, the mean yield increase from the AY to HY areas within fields was 19%. Region 1 of the "Grow for the Green" yield contest is as far north as Region 2 (Fig. 1), and similar to Region 2, the soils of Region 1 were derived from a mix of alluvial and loessial parent materials (USDA-NRCS, 2014b).

Across regions and yield areas, plant properties measured and calculated during the 2015 soybean growing season varied in scale and magnitude. For both yield areas, SGR from the mid-R5 to the mid-R6 sample dates ranged from 0.9 mg/seed/d in Region 2 to 5.2 mg/seed/d in Region 6. Consequently, EFP ranged from 23 d in Region 6 to 99 d in Region 2. The unusually low SGR observed in Region 2, which coincided with the abnormally long EFP also observed in Region 2, was outside the values of SGR and EFP previously reported in the literature, which range from 2.2 to 13.0 mg/seed/d and from 13 to 57 d, respectively (Van Roekel et al., 2015). A potential explanation for the atypical values is that the procedure used for separating seeds (i.e., gently blowing of mid-R5 seed) perhaps eliminated seed that would have been a component for final yield, but were too small after drying to be retained. Similar to SGR, the ASW for all average- and high-yield areas was lowest in Region 2 (78 mg) and the greatest ASW (162 mg) occurred in Region 4. Harvest index of both yield areas for each region ranged from 0.37 g/g in Region 3 to 0.72 g/g in Region 6, while seed N concentration ranged from 5.2% in Region 7 to 6.2% in Region 5. However, an HI of 0.72 g/g is greater than that previously documented for ultra-high-yield soybean in Arkansas, where Van Roekel and Purcell (2014) reported HI from 0.38 to 0.49 g/g and averaged 0.44 g/g over several cultivars and years. Perhaps some leaf tissue was lost during sampling and transport to account for the unusually large mean HI in Region 6.

Treatment Effects

Combined Effects of Yield Area and Growth Stage

Across regions, soybean HI, ASW, and seed K concentration differed ($p < 0.05$; Table 3) between yield areas among growth stages for the 2015 growing season. On average, HI was 77% greater at HM than at mid-R6 in both yield areas (Fig. 2), and was, on average, 275% greater at mid-R6 than at mid-R5 (Fig. 2). This result was expected, as HI is a measure of the weight of seed relative to the weight of the aboveground plant dry matter, and seeds gain weight from mid-R5 to HM (UACES, 2014).

Similar to HI, ASW in both yield areas, which did not differ (Fig. 2), was 29% greater at HM than ASW in both yield areas at mid-R6, which did not differ. Furthermore, ASW in the average-yield areas at mid-R6 (96 mg; Fig. 2) was greater ($p < 0.05$) than ASW in average-yield areas at mid-R5 (42 mg), which subsequently was greater ($p < 0.05$) than ASW in high-yield areas at mid-R5 (31 mg). Similar to HI, it was expected that ASW would increase from mid-R5 to HM. Although seeds continue to gain weight from formation until HM, ASW may decrease as a result of decreased cell division during the lag-phase of seed development, which decreases SGR, or during the linear phase of seed growth by shortening the EFP (Van Roekel et al., 2015).

Table 3. Analysis of variance summary of the effects of yield area (i.e., high- and average-yield area), growth stage (i.e., mid-R5, mid-R6, and harvest maturity), and their interaction on selected plant properties and seed concentrations measured across Arkansas in 2015.

Variable†	Yield area	Growth stage	Yield area × Growth stage
		---*p*---	
Yield	0.010	–	–
SGR	NS‡	–	–
EFP	NS	–	–
DMAC	NS	–	–
EFP2	NS	–	–
HI	0.007	< 0.001	0.040
Average seed weight	NS	< 0.001	0.023
Seed concentration			
C	0.040	< 0.001	NS
N	NS	< 0.001	NS
P	NS	< 0.001	NS
K	< 0.001	< 0.001	0.024
Ca	NS	< 0.001	NS
Mg	NS	< 0.001	NS
S	NS	0.048	NS
Na	NS	NS	NS
Fe	NS	< 0.001	NS
Mn	NS	0.002	NS
Zn	NS	< 0.001	NS
Cu	NS	< 0.001	NS
B	0.009	< 0.001	NS

† Units and abbreviations are as follows: Yield, lb/ac; SGR (seed growth rate), mg/seed/d; EFP (effective filling period, derived from SGR), d; DMAC (dry matter allocation coefficient), d^{-1}; EFP2 (derived from DMAC), d; HI (harvest index), g/g; Average seed weight, 0 mg; C, N, P, K, Ca, Mg, S, g/kg; Na, Fe, Mn, Zn, Cu, B, mg/kg.

‡ Effects and interactions that are not significant at the 0.05 level are represented by NS.

In contrast to HI and ASW trends among growth stages, seed K concentration was greater ($p < 0.05$; Fig. 2) in high-yield areas at mid-R5 (19.5 g/kg) than all other growth stage/yield area treatment combinations. Seed K concentration was also greater ($p < 0.05$; Fig. 2) in average-yield areas at mid-R5 (17.6 g/kg) than in both yield areas at mid-R6 and HM. Though the explanation for low seed K in HY areas is unknown, seed K would be expected to be greater in HY than in AY areas where yields were greater. Seed K concentration did not differ ($p > 0.05$; Fig. 2) between yield areas at mid-R6 and HM. Seed K concentrations at HM observed in this study were well below those reported previously by Parvej et al. (2015) under low-soil-K-fertility conditions across Arkansas, but greater than those reported by Farmaha et al. (2011) in Illinois averaged over soil-K fertility levels.

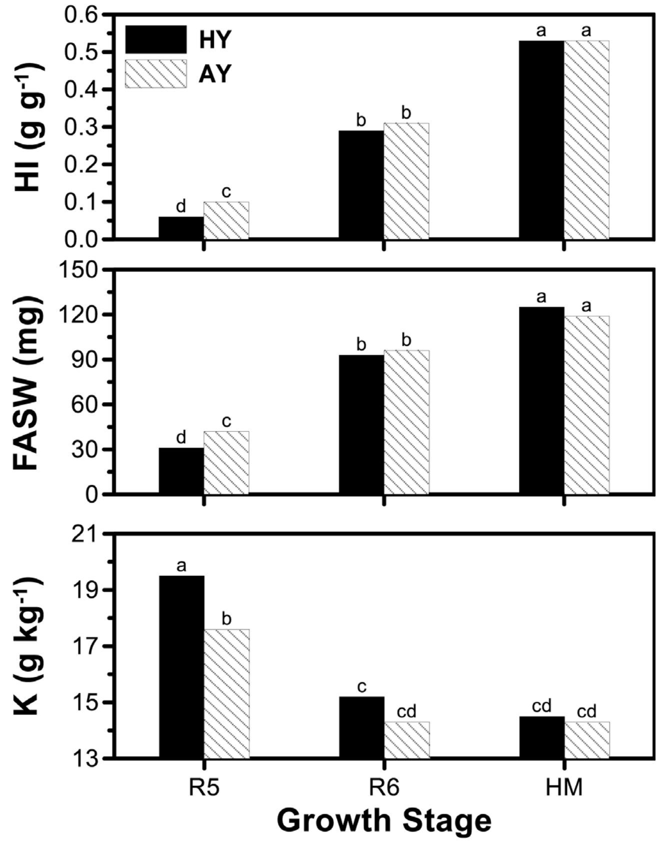

Fig. 2. Soybean harvest index (HI), average seed weight (ASW), and seed K concentration measured at the mid-R5 and mid-R6 growth stages (as defined by Fehr et al., 1971) and harvest maturity (HM) across regions in high-(HY) and average-yield (AY) areas of the “Grow for the Green” yield contest across Arkansas in 2015. Means with the same letter within each plant property are not different at α = 0.05.

Effect of Yield Area

For the 2015 soybean growing season, across regions, yield differed ($p = 0.010$; Table 3) between HY (88.3 bu/ac) and AY (74.4 bu/ac) areas (Table 1). This result was expected, as HY areas located in yield-contest field areas were managed more closely and intensely than AY areas for maximum productivity for contest purposes.

Across regions and averaged across growth stage, seed C and B concentrations differed ($p < 0.05$) between yield areas. Similar to yield, on average, seed B concentration was 10% greater in HY (31.8 mg/kg) than in AY (28.8 mg/kg) areas. Boron deficiencies have been identified in Arkansas (Ross et al., 2006), thus greater seed B in HY than in AY areas may indicate a need of more careful management of soil B. In contrast to yield and seed B, seed C concentrations were greater in AY (489.0 g/kg) than in HY (485.7 g/kg) areas, though the difference was small. Across regions, the physiological parameters of SGR, EFP, DMAC, ASW, and EFP2 did not differ ($p > 0.05$; Table 3) between yield areas. Likewise, seed N, P, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu concentrations also did not differ ($p > 0.05$; Table 3) between yield areas across regions and averaged across growth stages, perhaps indicating that micronutrients and associated foliar feeding are not required for high-yield soybeans.

Effect of Growth Stage

For the 2015 soybean growing season, across regions and averaged across yield area, seed N, C, P, Ca, Fe, Mn, Zn, Cu, and B concentrations differed ($p < 0.05$; Table 3) among soybean growth stages. Changes in seed nutrient concentration at different developmental periods generally followed one of three different patterns: (1) a decrease from R5 to R6 and HM (P, Fe, Ca, Mn, Cu, Zn, and B), (2) an increase from R5 to R6 and HM (N and C), and (3) a decrease from R5 to R6 followed by an increase to HM (Mg and S).

Seed P, Ca, Fe, Mn, Zn, Cu, and B concentrations (Table 4) all decreased from mid-R5 to HM. Furthermore, seed P, Ca, Fe, Mn, Zn, Cu, and B concentrations were all greater ($p < 0.05$) at the mid-R5 growth stage than at the other two growth stages and were, on average, 30% greater at mid-R5 than at HM. Seed Ca concentration was also 10% greater ($p < 0.05$) at mid-R6 than at HM. It is important to remember that this study merely analyzed seed nutrient concentrations and not contents. Similarly, it was assumed that contents of some nutrients did not decrease, but that contents of other nutrients increased, thus lowering concentrations of these nutrients at later growth stages. Uptake, partitioning, and remobilization of nutrients in soybean was studied from the 1930s to the 1970s (Bender et al., 2015); however, studies of within-seed tissue macro- and micronutrient concentrations are limited, as are studies of seed elemental concentrations throughout reproductive growth. With the exception of P, these nutrients have limited phloem mobility (Marschner, 1995), and the decrease in concentration perhaps resulted from a dilution effect as seed weight increased from mid-R5 to HM.

Seed N and C concentrations trended differently compared to numerous aforementioned seed nutrients (i.e., P, Ca, Fe, Mn, Zn, Cu, and B), where both increased numerically from mid-R5 to HM (Table 4). Seed N concentration was greatest ($p < 0.05$) at HM (57.6 g/kg), and was greater ($p < 0.05$) at mid-R6 (56.1 g/kg) than at mid-R5 (54.7 g/kg). Similar to seed N, seed C concentration was greatest at HM, which did not differ ($p < 0.05$) from that at mid-R6. Seed C concentration was, on average, 5% greater ($p < 0.05$) at HM and mid-R6 than at mid-R5. Nitrogen demand for soybean is greater than for other crops due to the high protein content, and this demand is met by accumulation as well as remobilization from vegetative tissue (Van Roekel et al., 2015). In Illinois on a silty clay loam, Bender et al. (2015) reported 50% of total N accumulation occurred after the beginning of R5, in addition to remobilization from leaf and stem N. In Gainesville, FL, Salado-Navarro et al. (1985) reported that as rates of N relocated from vegetative tissue to seed increased, rates of senescence of vegetative tissue also increased. Furthermore, seed N and C represent the ongoing accumulation of protein and oil during the seed-filling period.

Table 4. Soybean seed elemental concentrations, averaged across yield area, measured at the mid-R5 and mid-R6 growth stages (as defined by Fehr et al., 1971) and harvest maturity (HM) of the "Grow for the Green" yield contest across Arkansas in 2015.

Seed element	Growth stage Mid-R5	Mid-R6	HM
B (mg/kg)	36.8 a †	28.2 b	25.8 b
C (g/g)	473 b	494 a	495 a
Ca (g/kg)	3.6 a	2.6 b	2.4 b
Cu (mg/kg)	9.8 a	8.6 b	8.7 b
Fe (mg/kg)	55.6 a	50.5 b	48.8 b
K (g/kg)	1.8 a	1.5 b	1.4 b
Mg (g/kg)	1.8 a	1.7 b	1.8 a
Mn (mg/kg)	33.6 a	24.9 b	23.2 b
N (g/kg)	54.7 c	56.1 b	57.6 a
P (g/kg)	4.2 a	3.7 b	3.9 b
S (g/kg)	2.1 ab	2.0 a	2.1 b
Zn (mg/kg)	36.4 a	29.1 b	28.1 b

† Means with the same letter within a row are not different at $\alpha = 0.05$.

Seed Mg and S concentrations numerically decreased from mid-R5 to mid-R6 and subsequently increased to HM (Table 4). Seed Mg concentration was 9% greater ($p < 0.05$) at mid-R5 and HM, which did not differ, than at mid-R6. Similar to seed Mg, seed S concentration at HM (2.1 g/kg), which did not differ from that at mid-R5 (2.06 g/kg), was greater than seed S at mid-R6 (2.02 g/kg), which also did not differ from that at mid-R5. As with yield area, seed Na concentration did not differ among growth stages (Table 3).

In a meta-analysis, Rotundo and Westgate (2009) reported that differences in seed concentration primarily resulted from differential accumulation of individual seed components. This inhibition is a result of stress, either by drought, high temperatures, or low N fertility. In the same meta-analysis, water and temperature stresses decreased protein, oil, and residual content, while supplemental N increased protein content, had no effect on oil content, and decreased residual content (Rotundo and Westgate, 2009). While Slaton et al. (2013) reported fertilization and other management practices influenced seed nutrient concentration in Arkansas, Kleese et al. (1968) reported in Minnesota that soybean genotype may be more important than geographic location or year in determining accumulation of mineral elements in the seeds. However, the methods for determining elemental seed concentrations in Kleese et al. (1968) were different than those used in this study.

Correlations

For the 2015 soybean growing season, seed yield, SGR, EFP, dry matter allocation coefficient (DMAC), HI, effective filling period 2 (EFP2, calculated from DMAC), seed N concentration, ASW, and planting day of year (PDOY) were linearly correlated ($p < 0.05$; Table 5) with at least one other measured

Table 5. Pairwise correlations between yield (lb/ac), seed growth rate (SGR, mg/seed/d), effective filling period (derived from SGR; EFP, d), dry matter allocation coefficient (DMAC, d^{-1}), harvest index (HI, %), effective filling period 2 (derived from DMAC; EFP2, d), seed N concentration (%), average seed weight (ASW, mg), and planting day of year (PDOY, d).

Property †	SGR	EFP	DMAC	HI	EFP2	Seed N	ASW	PDOY
Yield	-0.31**	0.36**	-0.45***	0.09	0.45***	-0.28*	0.21	-0.62***
SGR	–	-0.86***	0.49***	0.42***	-0.20	0.40***	0.61***	0.72***
EFP	–	–	-0.55***	-0.29*	0.35**	-0.24*	-0.33**	-0.57***
DMAC	–	–	–	0.11	-0.85***	0.17	-0.08	0.40***
HI	–	–	–	–	0.31**	0.24*	0.49***	0.20
EFP2	–	–	–	–	–	-0.07	0.35**	-0.23
Seed N	–	–	–	–	–	–	0.43***	0.49***
ASW	–	–	–	–	–	–	–	0.44***

*** $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.**

† $n = 70$

or calculated variable. Yield was weakly negatively correlated with SGR ($p < 0.01$; $r = -0.31$) and seed N ($p < 0.05$; $r = -0.28$), while having a weakly positive correlation with EFP ($p < 0.01$; $r = 0.36$). Furthermore, yield had a moderately negative correlation ($p < 0.001$) with DMAC and PDOY ($r = -0.45$ and $r = -0.62$, respectively). Finally, yield had a moderately positive correlation ($p < 0.001$; $r = 0.45$) with EFP2. It was expected that SGR would not be strongly correlated with soybean yield, as variation in SGR may cause large differences in seed number that are not related to yield (Egli, 1998).

For the correlation of soybean yield with seed N concentration, enhanced productivity (i.e., greater yields) and greater seed quality (i.e., greater protein content) are traits that are often negatively correlated (Fabre and Planchon, 2000); therefore, it was expected that seed N would not be strongly correlated with yield. Fabre and Planchon (2000) reported that soybean protein content involved N_2 fixation efficiency during the entire reproductive growth period, while yield was more related to N assimilation at the beginning of reproductive growth and high N_2 fixation rates during the R6 growth stage.

As hypothesized, yield was negatively correlated with PDOY. The day of the year to plant has been studied by agronomists for many years and Egli and Cornelius (2009) reported a rapid decline in soybean yield when planting dates occurred after June 7 in Arkansas. Furthermore, research by the University of Arkansas demonstrated that soybean yield potential decreases by at least 0.5 bu/ac each day for every day sown after June 15 (UACES, 2014). In a regional analysis conducted by Egli and Cornelius (2009), no agricultural factor was demonstrated to affect soybean productivity more than planting date; however, planting date effects on yield can vary considerably due to deviations in rainfall amounts and distribution, as well as other environmental factors. Nevertheless, delaying planting beyond a critical date produces soybean that do not have the same yield potential as early plantings, and shifts reproductive growth of all soybean maturity groups into a less-favorable environment later in the growing season (Bastidas et al., 2008; Egli and Bruening, 2000; Egli and Cornelius, 2009). In a regional analysis by Salmerón et al. (2016), the soybean yield response to planting date was affected by location and the maturity group choices within a location.

Ideally, planting dates for HY and AY areas would have been the same for all regions to avoid confounding effects of PDOY with management differences between HY and AY areas. Except for Region 1, planting dates were the same or differed by no more than 2 d, and it is doubtful that a 1- or 2-d difference would impact yield provided that the one crop stand was not affected. For Region 1, there was a 7-d difference in planting date with the AY area being planted prior to the HY area. Although PDOY was negatively correlated with yield, factors other than PDOY obviously impacted yield as the later-planted (HY) area had yields 37.4 bu/ac greater than the earlier-planted (AY) area. Research modeling soybean response to PDOY and MG across the Midsouth indicates that there would be no expected yield difference in Region 1 for PDOY of 100 and 107 (Popp et al., 2016). Therefore, the differences in yield for the HY and AY areas were likely due to management factors other than slightly different PDOYs.

Seed growth rate had a moderately positive correlation ($p < 0.001$; Table 5) with PDOY ($r = 0.72$). It was expected that a later PDOY would lead to a greater SGR, as the EFP is reduced due to late plantings (Salmerón et al., 2016). This result is intuitive as well, since the mother plant would more quickly incorporate weight into seed if the window for translocation of weight material was shortened, but the fundamental driver is likely the photoperiod response that shortens the vegetative phase of the plant's life cycle.

Effective filling period, derived from SGR, had a moderately negative correlation ($p < 0.001$; Table 5) with PDOY ($r = -0.57$). Similar to SGR, it was expected that a later PDOY would lead to a reduction in the EFP because the amount of time for each growth stage of soybean would decrease (Bastidas et al., 2008; Salmerón et al., 2016). However, DMAC had a weakly positive correlation to PDOY ($p < 0.001$; $r = 0.40$).

Seed N had a moderately positive correlation ($p < 0.001$) to PDOY ($r = 0.49$). To our knowledge, research regarding correlations of seed N concentration with PDOY do not exist at present. Furthermore, ASW was moderately correlated ($p < 0.001$) to PDOY ($r = 0.44$). This coincides with research from Iowa that observed significant seed weight differences between the first three planting dates (March 30, April 13, and April 27) and the last three planting dates (May 10, May 30, and June 6) in a study investigating PDOY effects on yield (ISU, 2009). The last three planting dates produced seeds that were, on average, 11% heavier than seeds harvested from soybean planted at the first three dates (ISU, 2009).

Although six of eight variables had significant relationships with yield, no variable in this study was strongly correlated with yield (i.e., $r > \pm 0.75$); the only strong correlations were negative and were embedded in calculations (i.e., EFP with SGR and EFP2 with DMAC). However, the inverse relationship between yield and PDOY, as hypothesized, further validates past research studying PDOY. It appears that there are other factors (i.e., genetic, agronomic, and/or environmental) that should be further studied and may be greater correlated with yield.

Agronomic Implications

Across regions in the 2015 "Grow for the Green" soybean yield contest in Arkansas, measured and calculated plant properties that differed between high- and average-yield areas and across growth stages. Unexpectedly, in high- and average-yield areas, seed number increased from mid-R5 to mid-R6 and from mid-R6 to HM. However, as expected, HI and ASW increased from mid-R5 to mid-R6 and from mid-R6 to HM in both yield areas.

As hypothesized, the correlation analyses demonstrated the inverse relationship between yield and PDOY. Similar to what has been reported previously (Egli and Cornelius, 2009; Heatherly and Spurlock, 1999; Purcell et al., 2007; Salmerón et al., 2016), this study further validates the importance of PDOY and its effects on yield and verifies small plot research in Arkansas and the mid-south at the field scale. The trend of most yield-contest entries in Arkansas, dating back to 2002 (ASA, 2015a) and the majority in this field study (4 of 7 of the HY areas) is moving toward taking advantage of the early soybean production system (ESPS) system by planting early maturing group IV varieties earlier in the season to avoid late-summer droughts and lengthen the seed-filling period. By encompassing diverse landscapes and cropping systems, this research is valuable to soybean producers, whether or not entering areas into yield contests, across all of Arkansas.

Egli (1998) suggested that yield is predominantly source-limited in the real world of a producer's field. Therefore, to achieve ultra-high yields, management practices should focus on maximizing photosynthate production during the entire EFP to increase seed number, as well as limiting stresses during the EFP to extend the EFP and increase FASW (UACES, 2014). A better understanding of the physiological controls on soybean seed yield can guide effective management practices and growing conditions to maximize final yield.

Though the experimental design associated with this field study was not optimal to compare physiological characteristics and yield due to the yield areas having different varieties and planting dates, this study was meant to spark additional on-farm research that can extend the understanding of soybean yield limitations attributable to the environment in which soybean are grown. However, numerous additional agronomic characteristics were at least similar among yield areas, such that it was assumed that results were not overwhelmingly confounded by the inclusion of study sites and yield areas with different varieties and planting dates. Despite the experimental design issue and the lack of ability to make concise interpretations, results of this study clearly demonstrated that the soil environment plays a significant role in differential soybean response in HY and AY areas. Other factors (i.e., genetic, agronomic and/or environmental) should be further studied and may be better correlated with yield, which would further help soybean producers across Arkansas and elsewhere. Future research should mimic the approach used in this study by conducting studies in producer yield-contest-entered fields, despite the logistics being challenging.

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