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RESEARCH

Characterizing Genotype × Management Interactions on Soybean Seed Yield

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ABSTRACT

Increased soybean [*Glycine max* (L.) Merr.] commodity prices in recent years have generated interest in high-input systems to increase yield. The objective of this study was to evaluate the effects of current, high-yielding cultivars under high- and low-input systems on soybean yield and yield components. Research trials were conducted at 19 locations spanning nine states from 2012 to 2014. At each location, six high-yielding cultivars were grown under three input systems: (i) standard practice (SP, current recommended practices), (ii) high-input treatment consisting of a seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide (LCO); soil-applied N fertilizer; foliar LCO, fertilizer, antioxidant, fungicide and insecticide (SOYA), and (iii) SOYA minus foliar fungicide (SOYA-FF). An individual site-year yield analysis found only 3 of 53 (5.7%) site-years examined had a significant cultivar × input system interaction, suggesting cultivar selection and input system decisions can remain independent. Across all site-years, the SOYA and SOYA-FF treatments yielded 231 (5.5%) and 147 kg ha^{-1} (3.5%) more than the SP, and input system differences were found among maturity groups. Yield component measurements (seeds m^{-2}, seed mass, early-season and final plant stand, pods plant^{-1}, and seeds pod^{-1}) indicated positive yield responses were due to increased seeds m^{-2} and seed mass. While both high-input systems increased yield on average, grower return on investment (ROI) would be negative given today's commodity prices. These results further support the use of integrated pest management principles for making input decisions instead of using prophylactic applications to maximize soybean yield and profitability.

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Abbreviations: IPM, integrated pest management; LCO, lipo-chitooligosaccharide; MG, maturity group; ROI, return on investment; SOYA, high-input treatment consisting of university recommendations for fertilizer and herbicide programs; seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide; soil-applied nitrogen fertilizer; foliar lipo-chitooligosaccharide, fertilizer, antioxidant, fungicide, and insecticide; SOYA-FF, SOYA minus foliar fungicide; SP, standard practice (current university recommendations for fertilizer and herbicide programs).

Cultivar selection is the most important management decision soybean producers make each year (Furseth et al., 2011), and new cultivars, possessing various trait/genetic backgrounds are continuously being introduced into the market. Primary characteristics for cultivar selection include yield, disease and herbicide resistance traits, maturity group (MG), and cost, but

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other important traits include seed protein and oil concentration, mature plant height, seed size, and seed quality. Breeding efforts during the past 80 yr have considerably changed the physical traits of soybean cultivars available to producers, resulting in newer cultivars with greater yield potential, shorter height, later maturity, decreased lodging, and seeds with less protein and greater oil concentration (Rincker et al., 2014).

While cultivar selection, along with other agronomic practices, is important for maximizing yield, growers continue to seek other ways to increase yield. From 2009 to 2013, the average soybean price received increased by 40% from US\$0.37 to \$0.52 kg^{-1} (USDA-NASS, 2014). This, coupled with marketing information from agrichemical companies, spurred discussion about multiple input use (e.g., seed treatments, foliar fertilizers, and foliar fungicides). As a result, soybean growers have become interested in switching to a high-input based management approach using prophylactic applications of inputs in place of a traditional management system that typically uses low inputs and relies on integrated pest management (IPM) principles to warrant application. Unfortunately, this switch is being made in spite of limited validated data.

While studies have examined the effect of inputs individually on soybean yield, such as seed treatments, micronutrient fertilizers, foliar fungicides, and foliar insecticides (Dorrance et al., 2010; Enderson et al., 2015; Gaspar et al., 2014; Kyveryga et al., 2013), several studies have recently begun examining high-input based management systems and their effects on soybean yield and profitability. A study in Ohio evaluated the impact of an enhanced input system (*Rhizobia* inoculant, gypsum, Mn fertilizer, foliar insecticide, and foliar fungicide) compared to a traditional system which did not include these inputs (Bluck et al., 2015). The enhanced input system significantly increased yield compared to the traditional system in only 2 of 16 site-years. Moreover, break-even thresholds for the enhanced system were only found for 3 site-years. The authors also showed each input tested individually gave little yield response, and they attributed these results to good crop rotations, adequate fertility levels, and limited insect defoliation. Similarly, Orlowski et al. (unpublished data, 2016) examined 16 different input scenarios, which included inputs evaluated individually and multiple high-input systems, across 60 site-years from 2012 to 2014. They reported that increased input use significantly improved yield in <50% of the site-years examined compared to the standard management practice (i.e., untreated check). Their regional analysis showed the South (Arkansas, Kansas, Kentucky) and Central (Illinois, Indiana, Iowa) locations had limited responses to multiple input use, but the North (Michigan, Minnesota, Wisconsin) locations showed more response to the inputs used. Across all site-years, the high-input use systems increased yield by 0.15 to 0.30 Mg ha^{-1} (4–8%) more than the standard practice, but an economic analysis demonstrated these high-input systems had zero probability of breaking-even for each region and across all site-years. However, individual inputs, primarily the foliar insecticide, showed high break-even probabilities (>70%) for nearly all combinations of yield level and grain sale price when examined across all site-years.

Though Orlowski et al. (unpublished data, 2016) suggested high-input based management systems can increase yield but not often profitability, there is limited information regarding high-input use and its interaction with other agronomic practices (e.g., planting date, seeding rate, row spacing). Research in these areas could help fine-tune production practices to increase yield and profitability and could provide insight into why high-input based systems increase yield under certain management scenarios and not others. Two companion studies similar to the current study and Orlowski et al. (unpublished data, 2016) were conducted to determine if these high-input systems interact with row spacing and seeding rate to affect soybean yield. Wilson et al. (unpublished data, 2016) found no interaction between seeding rate and input system across average- and high-yielding environments. However, in low-yielding environments (<3.0 Mg ha^{-1}) at low seeding rates (plant populations), yields were maximized in the high-input treatments as compared to the control. The high-input system supported higher yields per plant in low productivity environments where plant populations were less than optimum. Haverkamp (2015) did not find a significant row spacing × input system interaction ($P \leq 0.05$) for soybean yield at five locations throughout Kansas and Minnesota. Furthermore, high-input systems only significantly increased yield at two of the five locations, and row spacing only influenced yield at one location. At that location (St. Paul, MN) narrow (19–25 cm) and medium (38–51 cm) row spacing produced the highest yields (Haverkamp, 2015).

While more information regarding high-input based management systems and their interaction with agronomic practices is becoming available, the interactions between input system and cultivar selection are still unknown. Therefore, the objective of this study was to quantify and evaluate cultivar × input system interactions on soybean yield and yield components.

MATERIALS AND METHODS

Field trials were conducted at 19 sites across nine states (Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, and Wisconsin) during the 2012 to 2014 growing seasons (Supplemental Table S1). The experimental design at each site was a randomized complete block with four replications. Treatments were arranged in a 6 × 3 factorial. Six soybean cultivars, representing high-yield potential cultivars suitable for each specific location, were chosen by the collaborating university agronomist from each state (Supplemental

Table 1. Product makeup and application information for each input level used during 2012 to 2014.

Product†	Input system‡ Standard practice	SOYA	SOYA-FF	Product component	Active ingredient	Application Growth stage	Product rate	Sprayer volume
Seed applied							mL kg seed^{-1}	
Acceleron§	–	+	+	fungicide	pyraclostrobin + metalaxyl	seed	1.04	–
Trilex 2000§ (2012)	–	+	+	fungicide	trifloxystrobin + metalaxyl	seed	0.65	–
EverGol Energy + Precise§ (2013–2014)	–	+	+	fungicide	prothioconazole + penflufen + metalaxyl	seed	0.65	–
Acceleron	–	+	+	insecticide	imidacloprid	seed	2.60	–
Poncho/VOTiVO	–	+	+	insecticide + nematistat	clothianidin + *Bacillus firmus*	seed	0.64	–
Optimize	–	+	+	LCO	lipo-chitooligosaccharide	seed	1.83	–
Foliar applied							kg ha^{-1}	–
Urea¶	–	+	+	nitrogen	46–0–0%N–P_2O_5–K_2O	V4	84	–
ESN	–	+	+	nitrogen	44–0–0%N–P_2O_5–K_2O	V4	84	–
			+				mL ha^{-1}	L ha^{-1}
Ratchet	–	+	+	LCO	lipo-chitooligosaccharide	V4-V6	292	140
Task Force 2	–	+	+	fertilizer	11–8–5–0.1–0.05–0.04–0.04–0.02–0.00025–0.00025% N–P_2O_5–K_2O–Fe–Mn–Zn–B–Co–Mo	R1	4676	140
Bio-Forge	–	+	+	antioxidant	N,N'-diformyl urea	R3	1169	187
Headline (2012)	–	+	–	fungicide	pyraclostrobin	R3	438	187
Priaxor (2013–2014)	–	+	–	fungicide	fluxapyroxad + pyraclostrobin	R3	585	187
Warrior II (2012)	–	+	+	insecticide	lambda-cyhalothrin	R3	140	187
Endigo (2013–2014)	–	+	+	insecticide	lambda-cyhalothrin + thiamethoxam	R3	292	187

† Acceleron (Monsanto Co., St. Louis, MO); Trilex 2000, EverGol Energy + Precise, Poncho/VOTiVO (Bayer Crop Science, Research Triangle Park, NC); Optimize (Novozymes, Brookfield, WI); ESN [environmentally smart nitrogen (polymer-coated urea)] (Agrium, Calgary, Alberta, Canada); Ratchet (Novozymes, Brookfield, WI); Task Force 2 (Loveland Products, Inc., Greeley, CO); Bio-Forge (Stoller USA, Inc., Houston, TX); Headline (BASF Corp., Florham Park, NJ) used in 2012; Priaxor (BASF Corp., Florham Park, NJ) used in 2013–2014; Warrior II used in 2012; Endigo used in 2013–2014 (Syngenta Crop Protection, LLC, Greensboro, NC).

‡ For all input systems, fertilizers and herbicides were applied according to university best management recommendations.

§ Acceleron fungicide was applied to all Monsanto Co. related cultivars [Asgrow, Channel, Kruger, Gold Country, Stewart (Supplemental Table S2)]; Trilex 2000 used in 2012 and EverGol Energy + Precise used in 2013–2014 was applied to all Pioneer Hi-Bred International, Inc. related cultivars (Supplemental Table S2).

¶ Treated with Agrotain [N-(n-butyl) thiophosphoric triamide] at 3.1 mL kg urea^{-1}.

Table S2). The six chosen cultivars were evaluated under three input systems: (i) SP (current university recommendations for fertilizer and herbicide programs), (ii) high-input treatment consisting of university recommendations for fertilizer and herbicide programs; seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide (LCO); soil-applied nitrogen fertilizer; foliar LCO, fertilizer, antioxidant, fungicide and insecticide (SOYA), and (iii) SOYA-FF. Products and rates used are listed in Table 1. Changes in cultivar selection for several locations across years were due to seed availability, and all cultivars used were resistant to glyphosate [*N*-(phosphonomethyl) glycine]. Plot size varied among states due to equipment differences, but all plots were at least 9.5 m^{-2} and were fully bordered. All locations were seeded at 432,000 seeds ha^{-1}. All fertilizer and weed control applications and rates at each location were made according to the respective university best management recommendations. Row spacing was primarily $\leq$38 cm, with some locations using 76 cm spacing (Supplemental Table S1).

Field operations and data collection were performed by personnel at each collaborating university for their respective locations. Early-season and final stand counts were recorded at V1–V2 and R8, respectively (Fehr and Caviness, 1977). Disease (percent incidence and severity) and insect (percent defoliation or number per plant) levels were assessed at R3 before the fungicide and insecticide application and again at R5 (Fehr and Caviness, 1977). At physiological maturity, the total number of plants and pods were recorded from 1 m of row from each plot. For harvest operations, grain weight and moisture was recorded from each plot, and moisture was adjusted to 130 g kg^{-1} content. Additionally, 450 g grain samples were collected from each plot and sent to the University of Minnesota-Twin Cities for seed mass measurements (grams 100^{-1} seeds). Seeds m^{-2} was calculated using yield and seed mass following the methods outlined by Board and Modali (2005).

Statistical Analysis

Statistical analyses were performed in SAS Version 9.3 (SAS Institute Inc., Cary, NC) using PROC MIXED. For yield, two separate analyses were performed. The first consisted of a mixed model ANOVA for individual site-years to determine the frequency of significant main effects and the cultivar × input system interaction. For this analysis, cultivar, input system, and the cultivar × input system interaction were considered fixed effects. Replication and the overall error term were considered random effects. Fifty-three site-years were evaluated. The Kansas locations (Manhattan, Rossville, and Scandia) in 2014 were not included due to misapplication of inputs, and the Waseca, MN, location in 2014 was not included due to excessive flooding. The second analysis consisted of a mixed model ANOVA at a regional and national scale across all 3 yr of the experiment. For this analysis, maturity group (e.g., 2.1, 3.2, 4.4, etc.) was used instead of cultivar for the regional analysis, and the whole maturity group (MG) (i.e., MG II, MG III, and MG IV) was used for the national analysis. Because only one cultivar from MG V was used during the duration of the experiment, it was removed from the nation-wide analysis. Fixed effects included maturity group, input system, and their interaction. Random effects included year, location(year), replication(location × year), and the overall error term. Degrees of freedom were calculated using the Kenward–Rogers method (Littell et al., 2006). Yield component (seeds m^{-2}, seed mass, early-season and final plant stands, pods $plant^{-1}$, and seeds pod^{-1}) analyses were performed only at the regional and national scale. Fixed and random effects for those analyses were similar to those used for the yield analysis. For all analyses, the level of significance was set at 5%, and pairwise means comparisons were conducted according to Fisher's protected LSD. The SLICE option in SAS was used to compare means of significant interactions.

RESULTS

Environment

Monthly average temperatures and total precipitation were variable among years for all locations compared to the respective 30 yr average (Supplemental Table S3). Increased temperatures and widespread drought were present across many of the field locations throughout much of the 2012 growing season. Average temperatures and above normal precipitation were experienced in May and June for many locations in 2013, but below normal temperatures and rainfall were observed throughout the remainder of the growing season. In 2014, precipitation was below normal when averaged across all locations, but high rainfall amounts were observed in June across many of the research sites. July temperatures and precipitation were below normal, but conditions returned to normal throughout the remainder of the growing season.

Yield

For the individual site-year analysis, in 2012 only 1 of 19 (5.3%) sites (KYhod) exhibited a significant cultivar × input system interaction, and cultivar and input system differences were found at 14 and 7 (73.7 and 36.8%) of 19 sites, respectively (Table 2). In 2013, only 1 of 19 (5.3%) sites (WIjan) showed a significant cultivar × input system interaction. Cultivar differences were found in 13 of 19 (68.4%) sites, and input treatment differences were found in 17 of 19 (89.5%) of sites (Table 2). Of the 17 sites which had significant input system differences, there were four sites (ARcol, ARnew, KSman, and KSsca) with unexpected means separation. For both AR locations, the SOYA-FF input treatment yielded significantly greater than both the SOYA and SP treatments. At both KS locations, the SP yielded higher compared to both SOYA and SOYA-FF (Table 2). In 2014, 1 of 15 (6.7%) sites analyzed (ARnew) revealed a significant cultivar × input system interaction, and cultivar and input system differences were found at 11 and 10 (73.3 and 66.7%) locations, respectively (Table 2). Across all 3 yr of the experiment, 3 of 53 site-years (5.7%) had a significant cultivar × input system interaction. Cultivar differences were found in 38 of 53 (71.7%) site-years, and input system differences were found in 34 of 53 (64.2%) site-years (Table 2). The SOYA input system had greater yield compared to the SP in 29 of 53 site-years (55%); whereas, SOYA-FF showed greater yield than the SP in 23 of 53 site-years (43%). The yield response of the SOYA treatment compared to the SP ranged from −646 to 702 kg ha^{-1} and ranged from −565 to 630 kg ha^{-1} for SOYA-FF compared to the SP. The SOYA input system yielded greater than the SOYA-FF system in 10 of 53 site-years (19%), and yield differences between SOYA and SOYA-FF ranged from −698 to 673 kg ha^{-1} (Table 2).

For the regional analysis, there was no evidence of a MG × input system interaction for each region, but MG and input system differences were found within all regions (Table 3). Means separation of the input systems were similar between the South (Arkansas, Kansas, Kentucky) and Central (Iowa, Illinois, Indiana) regions, but a larger response for the high-input systems was observed in the Central region. For the South region, the SOYA and SOYA-FF input treatments yielded 180 (4.3%) and 105 kg ha^{-1} (2.5%) more than the SP, respectively, and this same comparison for the Central region showed yield increases of 250 (6.2%) and 208 kg ha^{-1} (5.1%) for the SOYA and SOYA-FF treatments, respectively. However, no difference was found between both high-input systems within each region. In the North region (Michigan, Minnesota, Wisconsin), the SOYA and SOYA-FF input treatments yielded 319 (7.4%) and 228 (5.3%) kg ha^{-1} greater than the SP, respectively, but the SOYA treatment significantly increased yield by 91 (2.0%) kg ha^{-1} compared to its high-input counterpart.

At the national scale, there was evidence of a MG × input system interaction (Table 4). For each MG (II, III, and IV), both high-input systems yielded more than the SP, and the SOYA treatment yielded more than SOYA-FF (Fig. 1). However, the yield response of both high-input systems was different between MG. Yield differences between SOYA and the SP treatments were 288 (7.0%), 210 (5.0%), and 197 kg ha^{-1} (4.6%) for MG II, III, and IV, respectively. For SOYA-FF, differences compared to the SP were 230 (5.6%), 107 (2.6%), and 104 (2.4%) kg ha^{-1} for MG II, III, and IV, respectively. Furthermore, the SOYA treatment increased yield over SOYA-FF by 58 (1.3%), 103 (2.4%), and 93 (2.1%) kg ha^{-1} for MG II, III, and IV, respectively.

Yield Components

No evidence of a MG × input system interaction was found for seeds m^{-2} and seed mass at the regional level (Table 3). Maturity group and input system differences

Table 2. Location yield results, overall average yield, and input system yields by year, 2012 to 2014.

Location†	Year	*P* > *F*‡ Cultivar	Input system	Cultivar × Input System	Average yield	Input system§¶ Standard practice	SOYA	SOYA- FF
					kg ha^{-1}			
ARcol	2012	**	NS#	NS	3745	3688	3840	3670
	2013	**	***	NS	6024	5833b	5765b	6463a
	2014	***	***	NS	5517	5152b	5711a	5688a
ARnew	2012	***	NS	NS	2847	2776	2851	2932
	2013	**	*	NS	3596	3521b	3469b	3758a
	2014	*	*	**	4835	4589b	5058a	4717ab
IAfar	2012	***	NS	NS	4680	4529	4674	4836
	2013	NS	***	NS	4886	4607b	5118a	4933a
	2014	**	NS	NS	4584	4545	4557	4651
IAhum	2012	***	NS	NS	3538	3382	3587	3646
	2013	***	NS	NS	3271	3148	3288	3358
	2014	***	*	NS	3663	3533b	3783a	3673ab
ILmon	2012	NS	NS	NS	4592	4374	4645	4756
	2013	**	**	NS	4602	4444b	4711a	4650a
	2014	***	NS	NS	3895	3880	4003	3801
ILurb	2012	NS	NS	NS	2822	2733	2892	2841
	2013	***	***	NS	4450	4292b	4543a	4516a
	2014	***	NS	NS	4985	4893	5050	5013
INwan	2012	***	NS	NS	3629	3566	3600	3722
	2013	***	**	NS	4142	4022b	4209a	4195a
	2014	NS	***	NS	3989	3730b	4193a	4028a
INwla	2012	*	***	NS	4052	3610b	4312a	4229a
	2013	*	***	NS	5855	5602c	6072a	5891b
	2014	NS	***	NS	4349	4198b	4511a	4339b
KSman	2012	*	**	NS	4279	3908b	4477a	4451a
	2013	***	*	NS	3431	3689a	3291b	3258b
	2014	–	–	–	–	–	–	–
KSros	2012	NS	NS	NS	4753	4753	4954	4551
	2013	**	*	NS	3385	3264b	3642a	3249b
	2014	–	–	–	–	–	–	–
KSsca	2012	NS	NS	NS	5246	5305	5316	5116
	2013	NS	**	NS	2646	3050a	2404b	2485b
	2014	–	–	–	–	–	–	–
KYhod	2012	***	**	*	5356	5242b	5571a	5255b
	2013	NS	***	NS	4180	3968b	4444a	4128b
	2014	*	NS	NS	4181	4124	4168	4252
KYlex	2012	NS	**	NS	3479	3257b	3650a	3529a
	2013	**	**	NS	5376	5373ab	5715a	5042b
	2014	***	***	NS	3539	3358b	3679a	3581a
MIbre	2012	***	**	NS	4839	4778b	4989a	4750b
	2013	***	***	NS	3926	3769b	4013a	3992a
	2014	***	***	NS	3411	3167c	3641a	3426b
MIela	2012	*	NS	NS	3302	2937	3427	3542
	2013	NS	***	NS	4357	4043c	4668a	4359b
	2014	***	**	NS	4692	4588b	4806a	4794a
MNstp	2012	*	NS	NS	3645	3658	3629	3649
	2013	***	**	NS	5418	5234b	5568a	5451a
	2014	NS	NS	NS	4570	4386	4788	4537
MNwas	2012	**	NS	NS	3937	3983	3919	3909
	2013	*	***	NS	5106	4802b	5336a	5182a
	2014	–	–	–	–	–	–	–

(cont'd.)

Table 2. Continued.

Location†	Year	$P > F$‡ Cultivar	Input system	Cultivar × Input System	Average yield	Input system§¶ Standard practice	SOYA	SOYA- FF
					kg ha^{-1}			
WIarl	2012	***	***	NS	3829	3544b	3946a	3997a
	2013	NS	**	NS	4656	4501b	4782a	4686a
	2014	NS	*	NS	4990	4880b	5089a	5002ab
WIjan	2012	***	**	NS	4025	3812b	4108a	4155a
	2013	NS	NS	*	5193	5080	5229	5269
WIetr	2014	***	***	NS	5800	5562c	6068a	5772b

* Significant at the $P = 0.05$ probability level.

** Significant at the $P = 0.01$ probability level.

*** Significant at the $P = 0.001$ probability level.

† ARcol, Colt, AR; ARnew, Newport, AR; IAfar, Farley, IA; IAhum, Humboldt, IA; ILmon, Monmouth, IL; ILurb, Urbana, IL; INwan, Wanatah, IN; INwla, West Lafayette, IN; KSman, Manhattan, KS; KSros, Rossville, KS; KSsca, Scandia, KS; KYhod, Hodgenville, KY; KYlex, Lexington, KY; MIbre, Breckenridge, MI; MIela, East Lansing, MI; MNstp, St. Paul, MN; MNwas, Waseca, MN; WIarl, Arlington, WI; WIjan, Janesville, WI; WIetr, East Troy, WI.

‡ Probability of a larger F value by chance among cultivar, input system, and cultivar × input system effects.

§ For all input systems, fertilizers and herbicides were applied according to university best management recommendations; Standard Practice: current university recommendations for fertilizer and herbicide programs; SOYA: [high-input treatment consisting of university recommendations for fertilizer and herbicide programs; seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide; soil-applied nitrogen fertilizer; foliar lipo-chitooligosaccharide, fertilizer, antioxidant, fungicide, and insecticide]; SOYA-FF: SOYA minus foliar fungicide. Products and rates used are listed in Table 1.

¶ Values followed by the same letter for each input system are not statistically different at $P \leq 0.05$.

NS, no significant differences at $P \leq 0.05$.

were found within all regions for both variables, except for seeds m^{-2} in the South region. For seed mass, results were similar for each region. Both high-input systems produced increased seed mass compared to the SP, and the SOYA treatment increased seed mass compared to SOYA-FF (Table 3). However, input system differences were least in the South region and greatest in the North region. Differences between the SOYA and SP. treatments were 0.37 (2.2%), 0.47 (2.7%), and 0.60 (3.4%) g 100^{-1} seeds and 0.21 (1.3%), 0.26 (1.5%), and 0.29 (1.7%) g 100^{-1} seeds for SOYA-FF compared to the SP. within the South, Central, and North regions, respectively. Furthermore, the SOYA input treatment increased seed mass by 0.16 (1.0%), 0.21 (1.2%), and 0.31 (1.8%) g 100^{-1} seeds compared to SOYA-FF for the South, Central, and North regions, respectively. For seeds m^{-2}, both high-input systems produced approximately 3% more seeds m^{-2} compared to the SP within the North and Central regions (Table 3). At the national scale, there was no evidence of a MG × input system interaction for seeds m^{-2} and seed mass, but main effects for each variable were significant (Table 4). The SOYA and SOYA-FF treatments increased seeds m^{-2} by 2.5 and 1.7%, respectively, compared to the SP, with no difference observed between the two high-input systems. Seed mass was increased by 2.8 and 1.6% for the SOYA and SOYA-FF treatments, respectively, compared to the SP, and the SOYA treatment increased seed mass by 1.2% compared to SOYA-FF (Table 4).

Analysis of early-season and final plant stands, pods plant^{-1}, and seeds pod^{-1} were pursued in attempt to explain increased seeds m^{-2}. At the regional scale, there was evidence of a MG × input system interaction for early-season plant stand (North), final plant stand (South), and seeds pod^{-1} (South; Table 3). For early-season plant stand in the North region, the SOYA and SOYA-FF treatments increased plant stands by 15,069 (4.6%) and 17,654 (5.4%) plants ha^{-1} compared to the SP, respectively, but no difference was observed between the two high-input systems. For final plant stands, the SOYA and SOYA-FF input systems had 11,223 (3.7%) and 11,996 plants ha^{-1} (3.9%) more than the SP, respectively, in the North region. In the Central region, the SOYA treatment increased final plant stand by 8018 plants ha^{-1} (2.5%) compared to the SP, and it was the only high-input system to do so. Pods plant^{-1} differences between the input systems were only observed in the North and South regions (Table 3). In the North region, highest pods plant^{-1} was observed for the SP, and in the South region, highest pods plant^{-1} was found for the SOYA-FF treatment. Also within the South region, the SP and SOYA treatments showed increased seeds pod^{-1} compared to SOYA-FF (Table 3).

At the national scale, a MG × input system interaction was found for early-season and final plant stand and pods plant^{-1} (Table 4). No significant effects were observed for seeds pod^{-1}. For early-season plant stand, the SOYA and SOYA-FF treatments increased plant stands compared to the SP in MG II, with no difference found between both high-input systems (Fig. 1). For MG III, SOYA-FF was the only high-input treatment which significantly increased early-season plant stand compared to SP. In MG IV, SP exhibited higher early-season plants stands compared to both high-input systems. For final plant stands, both high-input systems increased stands compared to the SP within MG II and III, but no differences in fall plant stand were

Table 3. Regional analysis results, overall average, and input system averages for yield, seeds m^{-2}, seed mass, early-season and final plant stands, pods plant^{-1}, and seeds pod^{-1} across years, 2012 to 2014.

	$P > F$‡				Input system§¶		
Region†	Maturity group	Input system	Maturity group × input system	Average	Standard practice	SOYA	SOYA- FF
				Yield, kg ha^{-1}			
North	***	***	NS#	4,453	4290c	4609a	4,518b
Central	***	***	NS	4,223	4066b	4317a	4,274a
South	***	**	NS	4,247	4158b	4338a	4,263a
				Seeds m^{-2}			
North	***	***	NS	2574	2522b	2605a	2,598a
Central	***	***	NS	2423	2374b	2450a	2,453a
South	***	NS	NS	2607	2586	2638	2,612
				Seed mass, g 100^{-1} seeds			
North	***	***	NS	17.67	17.39c	17.99a	17.68b
Central	***	***	NS	17.49	17.21c	17.68a	17.47b
South	***	***	NS	16.47	16.22c	16.59a	16.43b
				Early-season plant stand, plants ha^{-1}			
North	***	***	*	337,078	326148b	341217a	343,802a
Central	***	NS	NS	340,442	341454	340846	339,720
South	***	NS	NS	348,130	349301	348593	346,239
				Final plant stand, plants ha^{-1}			
North	***	***	NS	312,202	304527b	315750a	316,523a
Central	***	*	NS	321,207	317165b	325183a	321,539ab
South	***	NS	NS	313,692	316199	312481	312,388
				Pods plant^{-1}			
North	**	*	NS	31.7	32.8a	31.2b	31.2b
Central	***	NS	NS	28.9	28.4	28.9	29.4
South	***	*	NS	46.3	43.9b	44.4b	48.3a
				Seeds pod^{-1}			
North	***	NS	NS	2.74	2.68	2.78	2.74
Central	**	NS	NS	2.77	2.75	2.77	2.80
South	**	*	*	2.12	2.24a	2.22a	2.08b

* Significant at the $P = 0.05$ probability level.

** Significant at the $P = 0.01$ probability level.

*** Significant at the $P = 0.001$ probability level.

† North: MI, MN, and WI; Central: IA, IL, and IN; South: AR, KS, and KY.

‡ Probability of a larger F value by chance among cultivar, input system, and cultivar × input system effects.

§ For all input systems, fertilizers and herbicides were applied according to university best management recommendations; Standard Practice: current university recommendations for fertilizer and herbicide programs; SOYA: [high-input treatment consisting of university recommendations for fertilizer and herbicide programs; seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide; soil-applied nitrogen fertilizer; foliar lipo-chitooligosaccharide, fertilizer, antioxidant, fungicide, and insecticide]; SOYA-FF: SOYA minus foliar fungicide. Products and rates used are listed in Table 1.

¶ Values followed by the same letter for each input system are not statistically different at $P \leq 0.05$.

NS, no significant differences at $P \leq 0.05$.

found among the input systems for MG IV (Fig. 1). Pods plant^{-1} results showed differences among the input systems for MG II and IV, but results were mixed between the two MG. No input system differences were found for pods plant^{-1} in MG III (Fig. 1).

DISCUSSION

From the individual site-year analysis, only 5.7% of 53 site-years showed a significant cultivar × input system interaction. Additionally, this interaction was not found to be significant at the regional level. Interestingly, this almost perfectly matches the 95% confidence interval used in which 5% of site-years would be expected to show a significant interaction. Therefore, these results suggest cultivar and input system decisions can remain independent for soybean growers across much of the soybean growing regions of the United States.

An economic analysis by Orlowski et al. (unpublished data, 2016) determined the marginal cost for the SOYA input treatment was \$341.26 ha^{-1} in 2012 and \$377.81 ha^{-1} in 2013–2014, and \$277.33 and \$281.73 ha^{-1} for the SOYA-FF treatment in 2012 and 2013–2014, respectively. Costs were different due to changes in foliar fungicide and insecticide products used those years. After evaluating the yield response needed to recover both marginal costs using a high grain sale price of \$0.55 kg^{-1}, similar to Orlowski

Table 4. Nation-wide analysis results, overall average, and input system averages for yield, seeds m^{-2}, seed mass, early-season and final plant stands, pods $plant^{-1}$, and seeds pod^{-1} across years, 2012 to 2014.

P > *F*†				Input system‡§		
Maturity group	Input system	Maturity group × input system	Average	Standard practice	SOYA	SOYA-FF
			Yield, kg ha^{-1}			
NS¶	***	*	4,306	4,180c	4,411a	4,327b
			Seeds m^{-2}			
***	***	NS	2,533	2,503b	2,565a	2,546a
			Seed mass, g 100^{-1} seeds			
***	***	NS	17.20	16.91c	17.38a	17.18b
			Early-season plant stand, plants ha^{-1}			
***	NS	***	337,154	335,571	337,662	338,147
			Final plant stand, plants ha^{-1}			
***	NS	NS	310,810	308,162	312,398	312,024
			Pods $plant^{-1}$			
***	NS	**	34.9	34.6	35.0	35.6
			Seeds pod^{-1}			
NS	NS	NS	2.56	2.53	2.58	2.55

* Significant at the $P = 0.05$ probability level.

** Significant at the $P = 0.01$ probability level.

*** Significant at the $P = 0.001$ probability level.

† Probability of a larger *F* value by chance among cultivar, input system, and cultivar × input system effects.

‡ For all input systems, fertilizers and herbicides were applied according to university best management recommendations; Standard Practice: current university recommendations for fertilizer and herbicide programs; SOYA: [high-input treatment consisting of university recommendations for fertilizer and herbicide programs; seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide; soil-applied nitrogen fertilizer; foliar lipo-chitooligosaccharide, fertilizer, antioxidant, fungicide, and insecticide]; SOYA-FF: SOYA minus foliar fungicide. Products and rates used are listed in Table 1.

§ Values followed by the same letter for each input system are not statistically different at $P \leq 0.05$.

¶ NS, no significant differences at $P \leq 0.05$.

et al. (unpublished data, 2016), the SOYA input treatment had a yield response large enough to at least break even at only four (7.5%) of the 53 site-years (INwla and KSman in 2012, ARcol in 2013, and ARcol in 2014). For the SOYA-FF treatment, only two locations (ILurb in 2013 and MIbre in 2014) produced yields large enough to cover the input costs. Orlowski et al. (unpublished data, 2016) also evaluated break-even probabilities using grain sale prices of \$0.44 and \$0.33 kg^{-1}, but results from this study showed return on investment (ROI) would be negative for both high-input systems under these lower grain sale prices.

When examining input system effects at the regional scale, both high-input systems increased yield compared to the SP within all regions, but only a response to fungicide use (i.e., SOYA vs. SOYA-FF) was found in the North region. At the national scale, input system differences were similar to the North region, and the addition of foliar fungicide increased yield by 84 kg ha^{-1}. Although prophylactic foliar fungicide use increased yield, disease levels were low to extremely low at all locations each year, and the disease levels observed would not have warranted fungicide use (data not shown). Low to moderate levels of sudden death syndrome (caused by *Fusarium virguliforme*) were found at the IAhum location all 3 yr and the IAfar location in 2014. However, the seed treatment and foliar fungicide products used in this study do not have efficacy on this particular fungal pathogen. Using the same economic analysis described above, the yield increases observed for both high-input systems were not large enough to recover the input costs within any of the three regions or at the national level (data not shown). This result is similar to Orlowski et al. (unpublished data, 2016) who showed break-even probabilities were 0% for the SOYA and SOYA-FF input treatments within the South and Central regions and at the nations scale (i.e., across all 60 site-years). The authors also reported the highest break-even probability found was 24% for the SOYA-FF input treatment in the North region under only a high yield (5.0 Mg ha^{-1}) and high grain sale price (\$0.55 kg^{-1}).

Based on the yield component analyses, there was evidence to determine which component(s) led to increased yield within each region and at the national scale. Seed mass results were consistent among all three regions. Both high-input levels increased seed mass compared to the SP, and the SOYA treatment increased seed mass compared to the high-input system without foliar fungicide. These results differ from Orlowski et al. (unpublished data, 2016). In that study, no differences between input systems were found in the South region. Furthermore, the SOYA treatment did not increase seed mass more than the SOYA-FF treatment in both the Central and North regions (Orlowski et al., unpublished data, 2016).

Increased yields are also often a direct result of increased seeds m^{-2} (De Bruin and Pedersen, 2008; Gaspar

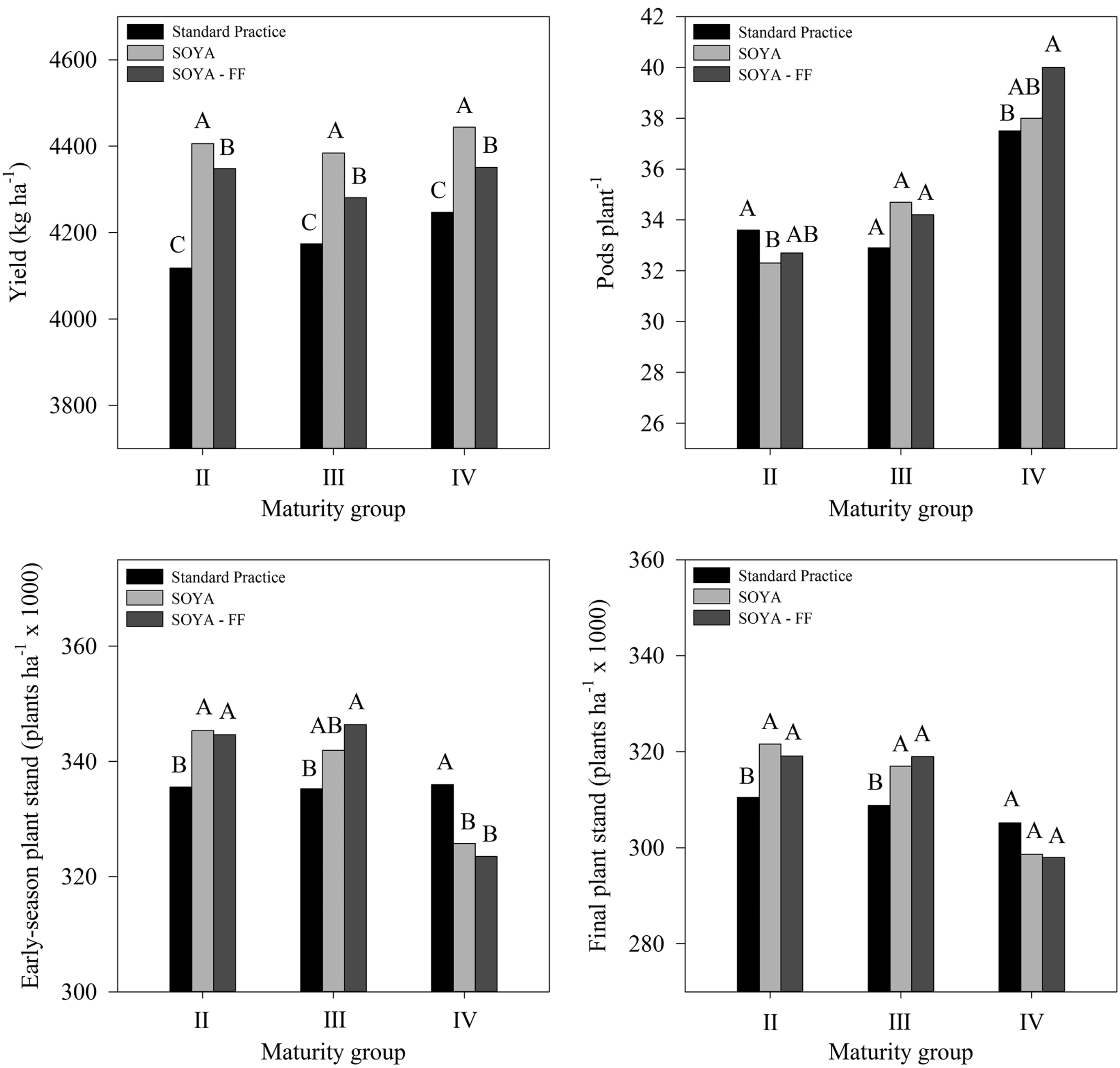

Fig. 1. Maturity group × input system results for soybean yield (top left), early-season plant stand (bottom left), final plant stand (bottom right), and pods plant^{-1} (top right) across all locations and years (n = 53) from 2012 to 2014. Values followed by the same letter for each input system within a maturity group are not statistically different at $P \leq 0.05$. For all input systems, fertilizers and herbicides were applied according to university best management recommendations; Standard Practice: current university recommendations for fertilizer and herbicide programs; SOYA: [high-input treatment consisting of university recommendations for fertilizer and herbicide programs; seed treatment fungicide, insecticide, nematistat, inoculant, and lipo-chitooligosaccharide; soil-applied nitrogen fertilizer; foliar lipo-chitooligosaccharide, fertilizer, antioxidant, fungicide, and insecticide]; SOYA-FF: SOYA minus foliar fungicide.

and Conley, 2015). In this study, the SOYA and SOYA-FF treatments increased seeds m^{-2} compared to the SP within the North and Central regions but not for the South region. Orlowski et al. (unpublished data, 2016) found similar results for the North and South regions but did not observe increased seeds m^{-2} for both high-input systems within the Central region. In the North region, final plant stands for both high-input systems was the primary component which increased seeds m^{-2}. This result can be attributed to the seed treatments used as part of both high-input systems, and this is supported by the early-season plant stand results in which both high-input systems also showed increased plant stands compared to the SP (Table 3). Orlowski et al. (unpublished data, 2016) also demonstrated similar final plant stand results for the North region. A study in Wisconsin examining soybean seed treatments across 30 environments found seed treatments containing fungicide + insecticide + nematicide components increased early-season plant stands compared to the untreated control, fungicide only, and fungicide + insecticide seed treatments by 10, 9, and 5.5%, respectively (Gaspar et al., 2014). In addition, the pods plant^{-1} results in the North region showed the SP treatment had increased pod production compared to both high-input systems. While there was a statistical difference, the observed differences could be considered minimal. Furthermore, lower plant stands for the SP explain why more pods plant^{-1} was observed for this input system compared to the high-input systems. Soybean plants at lower plant populations have been shown to produce more seed plant^{-1}, often by increases in pods plant^{-1} (Kahlon et al., 2011; Suhre et al., 2014). Therefore, the yield increases for both high-input systems in the North region were due to a combination increased plant stands and seed mass.

For the Central region, increased seeds m^{-2} also appeared to be due to increased final plant stands for both high-input systems. Unlike the North region, no input system differences were found for the early-season plant stands. The high-input systems may have reduced plant mortality during the growing season. Similar to the North region, yield increases in the Central region were due to a combination of increased final plant stands and seed mass.

In the South region, no differences were observed for early-season and final plant stands. Differences were found for pods plant^{-1} and seeds pod^{-1}, but the high-input levels did not consistently produce more pods plant^{-1} or seeds pod^{-1}. There also was no input system effect on seeds m^{-2}. Therefore, the increased yields observed for the high-input systems in the South region were most likely due to increased seed mass.

At the national scale, increased yield for both high-input systems was due to increased seeds m^{-2} and seed mass. Both high-input systems increased seeds m^{-2} and seed mass compared to the SP, and for seed mass, the SOYA treatment increased seed mass compared to SOYA-FF. These results mirror those of Orlowski et al. (unpublished data, 2016). For determining the source for increased seed number, there was evidence of a MG × input system interaction for early-season plant stand, final plant stand, and pods plant^{-1}. For early-season plant stands, both high-input systems increased plant stand compared to the SP for MG II and III, but highest plant stands were found for the SP within MG IV. For final plant stands, similar results were observed for MG II and III, but no input system differences were found for MG IV. Because increased plant stands for the SP were found for early-season plant stands but not final plant stands within MG IV, both high-input systems may again have reduced plant mortality throughout the growing season for MG IV. For the pods plant^{-1} results, the SOYA-FF treatment within MG IV was the only high-input system within all three MG to increase pods plant^{-1} compared to the SP. Even though this difference was found, the magnitude of the response is likely contributing little to the increased yield. Therefore, the increased yields for the high-input systems at the national scale were due to increased plant stands and seed mass for MG II and III and increased seed mass for MG IV.

CONCLUSIONS

Increased soybean commodity prices in recent years had growers interested in switching to an aggressive, high-input based approach instead of relying on a traditional management system based on integrated pest managment (IPM) principles. This switch was being made despite the lack of peer-reviewed validation of yield responses and knowledge of interactions with basic agronomic practices. This study was aimed at determining whether input systems interacted with cultivar selection to influence soybean yield and yield components. Because only 5.7% of 53 site-years exhibited a significant cultivar × input system interaction for yield, cultivar and input system choices can remain as independent management decisions. The high-input systems used in this study did increase yield at a majority of site-years, and this yield increase was often due to increased seeds m^{-2} and seed mass. However, for growers still interested in pursuing a high-input based management approach, results from this study showed the high-input systems only produced a positive ROI for <10% of the site-years. At the regional and nation scales, the ROI probability was reduced to zero. These results further support the active use of scouting and making input decisions based on sound IPM principles instead of using prophylactic applications to not only maximize yield but also grower profitability.

Supplemental Information Available

Supplemental information is available with the online version of this manuscript.

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References

Bluck, G.M., L.E. Lindsey, A.E. Dorrance, and J.D. Metzger. 2015. Soybean yield response to *Rhizobia* inoculant, gypsum, manganese fertilizer, insecticide, and fungicide. Agron. J. 107:1757–1765. doi:10.2134/agronj15.0094

Board, J.E., and H. Modali. 2005. Dry matter accumulation predictors for optimal yield in soybean. Crop Sci. 45:1790–1799. doi:10.2135/cropsci2004.0602

De Bruin, J.L., and P. Pedersen. 2008. Soybean seed yield response to planting date and seeding rate in the upper Midwest. Agron. J. 100:696–703. doi:10.2134/agronj2007.0115

Dorrance, A.E., C. Cruz, D. Mills, R. Bender, M. Koenig, G. LaBarge et al. 2010. Effect of foliar fungicide and insecticide applications on soybeans in Ohio. Plant Health Prog. doi: 10.1094/PHP-2010-0122-01-RS.

Enderson, J.T., A.P. Mallarino, and M.U. Haq. 2015. Soybean yield response to foliar-applied micronutrients and relationships among soil and tissue tests. Agron. J. 107:2143–2161. doi:10.2134/agronj14.0536

Fehr, W.R., and C.E. Caviness. 1977. Stages of soybean development. Iowa Coop. Ext. Serv. Spec. Rep. 80. Iowa State Univ., Ames.

Furseth, B.J., Y. Zhao, S.P. Conley, M. Martinka, and J. Gaska. 2011. Optimum soybean maturity groups for seed yield and quality in Wisconsin. Crop Manage. doi:10.1094/CM-2011-0622-01-RS.

Gaspar, A.P., and S.P. Conley. 2015. Responses of canopy reflectance, light interception, and soybean seed yield to replanting suboptimal stands. Crop Sci. 55:377–385. doi:10.2135/cropsci2014.03.0200

Gaspar, A.P., D.A. Marburger, S. Mourtzinis, and S.P. Conley. 2014. Soybean seed yield response to multiple seed treatment components across diverse environments. Agron. J. 106:1955–1962. doi:10.2134/agronj14.0277

Haverkamp, B.J. 2015. Systematic optimization of yield-enhancing applications in soybeans. M.S. thesis. Kansas State Univ., Manhattan.

Kahlon, C.S., J.E. Board, and M.S. Kang. 2011. An analysis of yield component changes for new and old soybean cultivars. Agron. J. 103:13–22. doi:10.2134/agronj2010.0300

Kyveryga, P.M., T.M. Blackmer, and D.S. Mueller. 2013. When do foliar pyraclostrobin fungicide applications produce profitable soybean yield responses? Plant Health Prog. doi:10.1094/PHP-2013-0928-01-RS.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. 2nd ed. SAS Inst., Cary, NC.

Rincker, K., R. Nelson, J. Specht, D. Sleper, T. Cary, S.R. Cianzio et al. 2014. Genetic improvement of U.S. soybean in maturity groups II, III, and IV. Crop Sci. 54:1–14. doi:10.2135/cropsci2012.12.0710

Suhre, J.J., N. Weidenbenner, S. Rowntree, E. Wilson, S. Naeve, S.P. Conley et al. 2014. Soybean yield partitioning changes revealed by genetic gain and seeding rate interactions. Agron. J. 106:1631–1642. doi:10.2134/agronj14.0003

USDA-NASS. 2014. Soybean survey. 1924–2014. USDA-NASS. http://quickstats.nass.usda.gov (accessed 29 Dec. 2014).