Published January, 2012

RESEARCH

Probability of Yield Response and Breaking Even for Soybean Seed Treatments

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ABSTRACT

Earlier soybean [*Glycine max* (L.) Merr.] planting coupled with increasing seed cost and commodity prices has led to an increase in the number of hectares treated with seed treatments. Ultimately, growers would like to know if applying such treatment is cost effective. Therefore, the objectives of this experiment were to quantify the effects of seed treatment on early season plant population and seed yield and investigate the probability that yield response covered the cost of the seed treatment. Trials were conducted in Wisconsin from 2008 to 2010 at nine locations each year to compare no seed treatment, mefenoxam + fludioxonil (ApronMaxx), and mefenoxam + fludioxonil + thiamethoxam (CruiserMaxx). Results indicated differences in early-season plant population due to cultivar and seed treatment and that seed yield was affected by a cultivar × seed treatment interaction. At a low seed treatment price, the percentage of environments where the probability of breaking even was >50% and ranged from 56 to 67%, while it ranged from 22 to 56% at a higher price. Both ApronMaxx and CruiserMaxx had positive response ratios of 1.5 ($p = 0.030$) and 2.9% ($p < 0.0001$), respectively, but responses were cultivar dependent. Given annual environmental variability, a general lack of field information regarding field history of pathogens or insects, and the high turnover rate of soybean cultivars, soybean seed treatments can be a cost-effective component to integrate into soybean production systems.

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Abbreviations: RR, relative response ratio; UTC, untreated control.

Over the past 10 yr, soybean [*Glycine max* (L.) Merr.] production has seen a dramatic planting date shift. Research has shown that earlier planting dates maximize yield (Robinson et al., 2009) and this has led many producers to sow soybean at planting dates similar to corn (*Zea mays* L.). Soybean is being sown in cooler and wetter soil conditions, increasing the probability that the seed will remain in the soil longer before emergence; this increases the risk of soybean seedlings being affected by early-season root rotting pathogens (Dorrance et al., 2009). The increase in no-tillage production may also increase the overall incidence o f these diseases.

One area of increasing debate regarding soybean production has been in the use of seed treatment fungicides and/or insecticides. Interest in this topic has developed for several reasons, including an increased emphasis on placing a high value on the soybean seed itself and recognition that seed can be used as a mechanism for delivering new inputs (Munkvold, 2009). As discussed by Munkvold (2009), some seed companies estimated that in 1996 approximately 8% of soybean seed was treated with a seed treatment while in 2008 it was approximately 30%. Anecdotal evidence suggests that the percentage of soybean seed being treated is even higher today, most likely greater than 50%.

Research on the use of seed treatments in soybean production has provided variable results. This is often due to both year and location (synonym: "environment") and whether there is

Published in Crop Sci. 52:351–359 (2012).
doi: 10.2135/cropsci2011.06.0311
Published online 31 Oct. 2011.

knowledge of targeted pathogens or insects. In Wisconsin, the use of seed treatments for control of *Phytophthora sojae* Kaufmann & Gerdemann in soybean in a single year and location trial that had a history of *P. sojae* Race 3 found that mefenoxam + fludioxonil (ApronMaxx RTA, Syngenta Crop Protection, Greensboro, NC) did not significantly affect plant stand or yield across the different soybean cultivars examined (Dorrance et al., 2009). In Brazil, Pereira et al. (2009) found that the use of the same compound was effective in reducing the level of anthracnose of soybean caused by *Colletotrichum truncatum* (Schwein.) Andrus & W.D. Moore. Cox et al. (2008) indicated that in the northeastern U.S., seed treatments were not a necessary component of the soybean production system. Ellis et al. (2011) indicated that there may be limited options for control of *Fusarium graminearum* Schwab, a pathogen that has recently been shown to infect soybean. Bradshaw et al. (2008) found that a seed treatment insecticide could effectively reduce the overwintering population of *Cerotoma trifurcata* (Forster) (bean leaf beetle) and could be integrated as part of a season-long management strategy for reducing both the insect population as well as the risk of *Bean pod mottle virus*, which is transmitted by this insect.

Nonetheless, from the producer's perspective, we hypothesize that control of seedling diseases or reducing insect pressure is only part of the reasons for using a seed treatment. Most producers are more interested in determining if the use of a seed treatment is cost effective, meaning that profitability is improved (Marra et al., 2003; Pannell et al., 2000). Producers are searching for increased yields that cover increased production costs (positive returns on investment). However, little is currently known about the magnitude of any physiological response to the use of a seed treatment (fungicide and/or insecticide) and the economic effect on profitability (Munkvold, 2009). Published evidence exists that suggests that the use of seed treatment fungicides can be cost effective, but the response is conditional, based on factors such as environment, seed quality, and soybean cultivar (Bradley, 2008; Poag et al., 2005). For example, Poag et al. (2005) evaluated several soybean fungicide seed treatments and found that, for what can be considered a small input cost (i.e., the cost of the seed treatment relative to other input costs), there is potential for increased profitability, although seed quality and soybean cultivar could affect the expected response. Bradley (2008) also found that the use of seed treatment fungicides on a single cultivar could be cost effective in North Dakota, especially in soil conditions that were cool and moist. However, this response was observed in only 33% of environments tested.

Given the increased interest in the use of seed treatments in soybean as well as the variable evidence in the current published literature for conditions where use is most effective, further research is needed to provide producers with information that best reflects the probability that the use of seed treatments is cost effective. Recently, several researchers have used Bayesian statistical approaches to quantify the probability that the use of an agricultural input or management tactic will be cost effective (De Bruin et al., 2010; Johnson et al., 2009; Munkvold et al., 2001). This approach can be very useful to reduce what Bolker (2008) describes as the "true" versus "false" interpretation of *p*-values from traditional ANOVA approaches as well as provide producers with a measure of the likelihood that using an input or management tactic can be cost effective in the long run.

In this paper, our objectives were to (i) quantify the effect of seed treatment on early-season plant population and seed yield and (ii) determine the probability of growers breaking even when applying seed treatments. To accomplish these objectives we examined the use of two commonly applied seed treatments (ApronMaxx RFC [Syngenta Crop Protection] or CruiserMaxx [Syngenta Crop Protection]) on four soybean cultivars grown under a wide array of production situations in Wisconsin. These two products differ in their relative cost of application per unit. We illustrate the use of both a multienvironment analysis (Littell et al., 2006) as well as a Bayesian analysis (Gelman et al., 2004) that integrates the cost of the seed treatment, grain sale price, and actual yield (i.e., the amount of harvested grain) to determine the probability of a seed treatment resulting in a yield response that covers the cost of the application (i.e., breaking even).

MATERIALS AND METHODS

Field trials were established at nine locations in Wisconsin (Table 1) from 2008 to 2010 for a total of 27 environments. Each trial was arranged in a randomized complete block design with four replications of three seed applied treatments, ApronMaxx RFC (mefenoxam [0.0057 mg a.i. per seed] and fludioxonil [0.0039 mg a.i. per seed]), CruiserMaxx (thiamethoxam [0.0762 mg a.i. per seed], mefenoxam [0.0057 mg a.i. per seed], and fludioxonil [0.0039 mg a.i. per seed]), and an untreated control. The fungicide components in each product target the following organisms: *Pythium*, *Phytophthora*, *Fusarium*, and *Rhizoctonia* spp. Also listed on the label is suppression for seed-borne *Sclerotinia* and *Phomopsis* spp. The insecticidal component (thiamethoxam) targets a range of insect pests, with the primary targets in Wisconsin being aphids, bean leaf beetle, and seed corn maggot. Each product was applied to each of four soybean varieties per year (2008: AG1403 [Monsanto, St. Louis, MO]; HS2025 [Growmark, Inc., Bloomington, IL]; and KB177RR and KB194RR [Kaltenberg Seed Farms, Waunakee, WI]; 2009: AG1403; FS20R80 [Growmark, Inc.]; and KB177RR and KB194RR; 2010: AG1403; HS20R80; and P91Y70 and P91Y90 [Pioneer Hi-Bred Intl., Inc., Johnston, IA]). Lack of cultivar consistency across years was due to limited seed availability and cultivar turnover. All soybean cultivars were resistant to glyphosate [*N*-(phosphonomethyl) glycine].

Planting occurred during May in each year (Table 1). Plots were six rows wide and planted to a length of 7.6 m at a rate of 425,000 seeds ha^{-1} in 38 cm row spacing. Plots were later shortened to 6.4 m and the middle four rows of each plot were harvested at maturity with a plot combine (Almaco SPC-40,

Table 1. Field characteristics of the seed treatment trials (2008–2010) in Wisconsin.

Year	Location	Environment†	Latitude and longitude	Planting date	Soil type‡	Clay§	OM¶	pH	P	K	Precipitation#
						%	g kg^{-1}		— mg kg^{-1} —		mm
2008	Arlington	2801	43°18'8" N, 89°20'8" W	8 May	Plano silt loam	18 to 27	3.9	6.9	62	131	2.5
	Janesville	2802	42°43'33" N, 89°1'17" W	6 May	Plano silt loam	18 to 27	3.9	6.6	54	189	27.9
	Lancaster	2803	42°49'49" N, 90°47'21" W	10 May	Fayette silt loam	24 to 32	2.3	6.4	26	115	22.6
	Fond du Lac	2804	43°43'34" N, 88°34'18" W	9 May	Pella silt loam	27 to 35	3.9	6.5	29	97	6.9
	Galesville	2805	44°4'27" N, 91°19'58" W	12 May	Downs silt loam	24 to 32	3.6	5.9	52	215	8.6
	Hancock	2806	44°7'10" N, 89°32'7" W	8 May	Plainfield sand	0	0.7	6.1	37	54	21.6
	Chippewa Falls	2807	44°57'0" N, 91°21'1" W	14 May	Sattre loam	18 to 23	2.1	6.4	37	108	5.8
	Marshfield	2808	44°38'29" N, 90°7'59" W	20 May	Withee silt loam	18 to 25	3.4	6.3	59	201	43.2
	Seymour	2809	44°31'25" N, 88°19'46" W	16 May	Solona silt loam	15 to 23	2.8	7.2	22	161	8.4
2009	Arlington	2901	43°18'8" N, 89°20'8" W	6 May	Plano silt loam	18 to 27	3.6	6.6	75	321	7.6
	Janesville	2902	42°43'33" N, 89°1'17" W	18 May	Plano silt loam	18 to 27	3.7	6.9	48	170	27.9
	Lancaster	2903	42°49'49" N, 90°47'21" W	19 May	Fayette silt loam	24 to 32	2.3	7.2	36	104	47.8
	Fond du Lac	2904	43°43'34" N, 88°34'18" W	20 May	Pella silt loam	27 to 35	5.3	6.5	15	94	14.7
	Galesville	2905	44°4'27" N, 91°19'58" W	11 May	Downs silt loam	24 to 32	3.7	5.8	19	146	4.6
	Hancock	2906	44°7'10" N, 89°32'7" W	7 May	Plainfield sand	0	0.7	6.6	70	105	23.6
	Chippewa Falls	2907	44°57'0" N, 91°21'1" W	14 May	Sattre loam	18 to 23	2.0	6.3	28	88	2.3
	Marshfield	2908	44°38'29" N, 90°7'59" W	12 May	Withee silt loam	18 to 25	2.9	7.0	36	98	13.0
	Seymour	2909	44°31'25" N, 88°19'46" W	21 May	Solona silt loam	15 to 23	2.7	7.5	16	67	54.6
2010	Arlington	10111	43°18'8" N, 89°20'8" W	3 May	Plano silt loam	18 to 27	3.1	6.5	64	145	67.0
	Janesville	10112	42°43'33" N, 89°1'17" W	3 May	Plano silt loam	18 to 27	3.2	6.6	51	148	70.4
	Lancaster	10113	42°49'49" N, 90°47'21" W	4 May	Fayette silt loam	24 to 32	1.6	6.8	22	79	72.9
	Fond du Lac	10114	43°43'34" N, 88°34'18" W	19 May	Pella silt loam	27 to 35	3.8	6.8	30	82	4.8
	Galesville	10115	44°4'27" N, 91°19'58" W	5 May	Downs silt loam	24 to 32	3.4	6.1	40	168	70.9
	Hancock	10116	44°7'10" N, 89°32'7" W	6 May	Plainfield sand	0	0.6	5.7	102	73	63.0
	Chippewa Falls	10117	44°57'0" N, 91°21'1" W	17 May	Sattre loam	18 to 23	2.9	6.1	33	103	0.5
	Marshfield	10118	44°38'29" N, 90°7'59" W	18 May	Withee silt loam	18 to 25	2.7	6.1	52	128	19.8
	Seymour	10119	44°31'25" N, 88°19'46" W	20 May	Solona Silt Loam	15 to 23	2.5	7.0	19	70	1.3

†Environment represents the unique year and location combination. The numbers were used for coding a study site each year.

‡Soil type from soil web survey. Plano: fine-silty, mixed, superactive, mesic Typic Argiudolls; Fayette: fine-silty, mixed, superactive, mesic Typic Hapludalfs; Pella: fine-silty, mixed, superactive, mesic Typic Endoaquolls; Downs: fine-silty, mixed, superactive, mesic Mollic Hapludalfs; Plainfield: mixed, mesic Typic Udipsamments; Sattre: fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Mollic Hapludalfs; Withee: fine-loamy, mixed, superactive, frigid Aquic Glossudalfs; Solona: coarse-loamy, mixed, superactive, frigid Aquic Argiudolls.

§Range in percent clay basis for this soil type.

¶OM, organic matter. pH, K, and P values are a composite of individual sites each year.

#Cumulative precipitation within the first 10 d of planting. Precipitation data collected from the Wisconsin State Climatology office (Madison, WI).

ALMACO, Nevada, IA) to measure yield. Seed yield was adjusted to a moisture content of 130 g kg^{-1}.

Soil samples were taken at planting and analyzed for soil pH, organic matter, and macronutrients at the University of Wisconsin Soil and Plant Analysis Laboratory (Madison, WI) (Table 1). In-season weed and insect control was done according to University of Wisconsin recommendation based on best management practices. Population data were collected by counting the total number of plants in a 2.32 m^2 section of each plot when the plants reached the V2 to V3 growth stage (Fehr and Caviness, 1977).

Statistical Analyses

Two types of statistical analysis were conducted. All analyses were conducted in SAS v. 9.2 (SAS Institute, 2008). The first was a multienvironment analysis to examine the effect of soybean cultivar and seed treatment on early-season plant population and yield (Littell et al., 2006). In this analysis, soybean cultivar, seed treatment, and the interaction were considered fixed effects while environment, replication(environment), environment × variety, environment × seed treatment, environment × cultivar × seed treatment, and the overall error term were considered random effects (Littell et al., 2006). The level of significance was set at 5%, and means comparisons were based on Fisher's protected LSD. Degrees of freedom were calculated using the Kenward-Rogers method (Littell et al., 2006). The slice option in SAS was used to examine interactions of soybean cultivar and seed treatment.

The second analysis was a Bayesian economic analysis to quantify the probability that the use of a seed treatment would be cost effective, meaning that the cost of the product was covered by an expected relative increase in yield (measured as a percentage increase). This analysis was conducted in three stages, and the methods applied were similar to De Bruin et al. (2010), Johnson et al. (2009), and Munkvold et al. (2001). The first stage analysis was the construction of 27 individual ANOVAs for each environment to obtain LSMean (least square mean) estimates for each treatment component of cultivar, seed treatment, and the interaction of cultivar and seed treatment. These analyses were conducted using PROC MIXED (SAS Institute, 2008).

From the estimated LSMean values for each cultivar–seed treatment combination, a response ratio was calculated

Table 2. Components of the Bayesian economic analysis, including seed treatment price, grain sale price, and actual yield.

Seed treatment price†	Grain sale price	Actual yield‡
US\$ ha^{-1}	US\$ kg^{-1}	kg ha^{-1}
9	0.22	2690
24	0.33	4035
	0.44	5380

†Seed treatment prices reflect the approximate current cost for ApronMaxx (US\$9 ha^{-1}) or CruiserMaxx (US\$24 ha^{-1}).

‡Actual yields represented a range of seed yield observed over the period of this study (2008–2010).

Table 3. Soybean seed yield response to seed treatment relative to cultivar across all location–years.

Cultivar	UTC†	ApronMaxx	CruiserMaxx
	Seed yield (kg ha^{-1})		
AG1403	3929	3833	3951
HS2025	4096	4085	4038
HS20R80	3959	4104	4049
KB177RR	3777	3879	4015
KB194RR	3702	3840	3905
P91Y70	3753	3803	3845
P91Y90	3984	3964	3983
LSD (0.05)		190	

†UTC, untreated control.

within a cultivar as yield$_{\text{seed treatment}}$/yield$_{\text{untreated control}}$ (the yield observed with the use of a seed treatment divided by the yield in the untreated control). This ratio calculation is similar to one approach commonly applied in meta-analysis (Borenstein, 2009) when summarizing data from multiple published or unpublished research trials. To enable a direct test of the null hypothesis that response ratio for an environment, cultivar, seed treatment, or the interaction of cultivar and seed treatment was 0, each response ratio was standardized by subtracting 1. This bounded values between –1 and 1 (e.g., –100 and 100% multiplying out to obtain a percentage).

The second stage analysis involved conducting another ANOVA using PROC MIXED (SAS Institute, 2008); this was done to estimate the effect of each factor component of the study. At this stage, environment was considered a blocking factor and was also considered a fixed effect to examine factors that may have led to differences in response across locations and years. Cultivar, seed treatment, and the interaction of cultivar and seed treatment were also considered fixed effects, while the overall error term was the only random effect. Due to the unbalanced number of replicates for each soybean cultivar, degrees of freedom were calculated based on the Kenward-Rogers method (Littell et al., 2006). In addition to the direct test of hypothesis for individual response ratios described earlier, LSMeans were determined for each seed treatment product to conduct the economic analysis in the third stage of the analysis.

The third stage analysis was a Bayesian economic analysis. A combination of seed treatment price, grain sale price, and actual yield were examined (Table 2). First, a cost relative yield was calculated as:

$$\text{Cost relative yield} = \text{ST}/(\text{GSP} \times \text{AY}),$$

adapted from De Bruin et al. (2010), where ST is the seed treatment cost (US\$ ha^{-1}), GSP is the grain sale price (\$ kg^{-1}), and AY is the actual yield (kg ha^{-1}). The cost relative yield is unitless and can be thought of as the minimum percentage (e.g., yield gain) needed to cover the cost of applying a seed treatment under different potential grain sale prices and actual yields. Observed relative yields (standardized) were subtracted from the cost relative yield and the standard error used for each comparison test was the standard error for each combination of environment, cultivar, seed treatment, or interaction of cultivar and seed treatment. This enabled comparisons based on the *t*-distribution. In addition, this analysis is based on an a priori hypothesis that a grower would have minimal information regarding the effect of a seed treatment. In a Bayesian framework, this is considered a noninformative prior (Gelman et al., 2004). When the prior is noninformative and the data distribution is *t*, the posterior distribution is also a *t*-distribution. Therefore, we were able to calculate the probability that the use of a seed treatment was cost effective by using the SAS PROBIT function (SAS Institute, 2008) to estimate a one-tail probability.

RESULTS AND DISCUSSION

Effect of Cultivar and Seed Treatments Across Years and Locations

Soybean cultivar ($p < 0.001$) and seed treatment ($p = 0.04$) affected early-season (V2–V3) soybean population. Cultivar mean plant populations ranged from 254,000 to 290,000 plants ha^{-1} when averaged across seed treatments. For seed treatments, mean plant populations ranged from 264,000 to 276,000 plants ha^{-1} when averaged across cultivars. CruiserMaxx increased stand 3% over the untreated control (UTC) whereas no early-season population difference was noted between the UTC and ApronMaxx. Although differences in early-season soybean population were noted among main effects, biologically they likely had minimal impact on seed yield since all plant populations were above levels required to achieve maximum seed yield (De Bruin and Pederson, 2008).

Results of cultivar × seed treatment interactions ($p = 0.001$) for seed yield are presented in Table 3. The response to seed treatments differed by cultivar. Specifically, there were differences noted for AG1403, HS20R80, KB177RR, and KB194RR when examining the interactions based on the SLICE option in SAS (SAS Institute, 2008) ($p < 0.05$). For seed treatment, there was evidence that the response differed across cultivars for the UTC and ApronMaxx ($p < 0.001$) while the response was more consistent for CruiserMaxx ($p = 0.2794$). Seed yield and soybean population results suggest that seed treatments can be effective; however, the response was a function of cultivar.

From an agronomic management perspective, plant population (i.e., stand) and seed yield are two of the most important factors to consider when deciding to use a seed treatment. However, given today's current seed costs coupled with higher commodity prices and market pressure to use seed treatment technologies, many growers have relegated this decision from yield to "insurance."

Table 4. Relative response ratio and the probability of breaking even when using a seed treatment at a lower price per unit across environments.

Environment†	RR‡	p	ST§ = US$9.9 ha^{-1}; GSP = US$0.22 kg^{-1} AY = 2690	AY = 4035	AY = 5380	ST = US$9.9 ha^{-1}; GSP = US$0.33 kg^{-1} AY = 2690	AY = 4035	AY = 5380	ST = US$9.9 ha^{-1}; GSP = US$0.44 kg^{-1} AY = 2690	AY = 4035	AY = 5380
			kg ha^{-1}								
2801	4.7	0.055	89	92	94	93	95	95	94	95	96
2802	–0.4	0.876	20	27	31	27	32	35	31	35	37
2803	–2.6	0.500	9	13	15	13	16	18	15	18	20
2804	–6.4	0.009	0	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.3
2805	–2.1	0.386	6	9	11	9	12	14	11	14	15
2806	–1.0	0.687	14	19	23	19	24	26	23	26	28
2807	3.2	0.187	74	81	84	81	85	87	84	86	88
2808	–1.8	0.458	8	11	14	11	15	17	14	17	18
2809	5.4	0.028	94	96	97	96	97	98	97	98	98
2901	4.1	0.089	84	89	91	89	92	93	91	93	94
2902	0.8	0.742	35	44	49	44	51	54	49	54	56
2903	2.5	0.303	63	71	75	71	76	79	75	79	80
2904	4.4	0.066	87	92	93	92	94	95	93	95	95
2905	11.6	<0.001	100	100	100	100	100	100	100	100	100
2906	6.4	0.008	98	99	99	99	99	99	99	99	99
2907	–0.6	0.799	17	24	27	24	29	31	27	31	33
2908	3.3	0.173	75	82	84	82	85	87	84	87	88
2909	1.2	0.605	43	52	57	52	58	61	57	61	63
10111	3.5	0.148	78	84	86	84	87	89	86	89	90
10112	3.6	0.132	79	85	88	85	89	90	88	90	91
10113	3.6	0.132	79	85	88	85	89	90	88	90	91
10114	0.2	0.929	27	35	40	35	41	44	40	44	47
10115	0.2	0.946	27	35	39	35	41	44	39	44	46
10116	1.0	0.688	39	48	52	48	54	57	52	57	59
10117	3.5	0.147	78	84	87	84	87	89	87	89	90
10118	1.9	0.440	53	62	66	62	68	71	66	71	73
10119	8.6	0.001	100	100	100	100	100	100	100	100	100

†Environment represents the unique year and location combination. The numbers were used for coding a study site each year.

‡RR, relative response ratio, a comparison of yields with a seed treatment to the untreated check.

§ST, seed treatment price; GSP, grain sale price; AY, actual yield.

Therefore, given the variability in cultivar yield response to seed treatments combined with both decreased soybean cultivar lifespan and rapid deployment of new soybean traits, it is critical to capture the probability that at worst a grower will break even on their seed treatment investment to improve current management recommendations.

Probability of Breaking Even with the Use of Seed Treatments

In Tables 4 through 9, relative response ratios (RRs) are presented for direct tests of the null hypothesis that individual RRs were not different from zero as well as the probability that the break-even point is achieved across environments, cultivar, seed treatment, and the interaction of cultivar and seed treatment. There was evidence of differences in response to cultivar and seed treatments across environments ($p = 0.0008$). Out of the 20 environments where the RR was >0, five were significantly different from 0 at the 5% level and three were considered marginal ($0.10 > p > 0.05$) (Table 4). While there were seven environments in which the relative response was negative, in only one environment (2804) was this difference significant (–6%). Overall, these results were similar to those of Bradley (2008), who observed positive yield responses in 29% of environments for at least one fungicide seed treatment tested.

The probability that the cost of applying a seed treatment was recovered within a given environment (i.e., breaking even) varied by the seed treatment price, grain sale price, and actual yield (Tables 4 and 5). When seed treatment cost and grain sale price were low, the percentage of environments that had a probability of breaking even >50% ranged from 56 to 63% across different actual yields. As grain sale price shifted to higher levels, the percentage of environments with a probability of breaking even >50% ranged from 59 to 67% and there were no differences between the two grain sale prices. When the seed treatment price was higher ($24.7 ha^{-1}), the percentage of environments where the probability of breaking even was >50% and ranged from 22 to 52%, 48 to 56%, and 52 to 56% across different actual yields and for grain sale prices of $0.22, 0.33, and 0.44 kg^{-1},

Table 5. Probability of breaking even when using a seed treatment at a higher cost per unit across environments.

Environment	ST‡ = US$24.7 ha⁻¹; GSP = US$0.22 kg⁻¹			ST = US$24.7 ha⁻¹; GSP = US$0.33 kg⁻¹			ST = US$24.7 ha⁻¹; GSP = US$0.44 kg⁻¹		
	AY = 2690	AY = 4035	AY = 5380	AY = 2690	AY = 4035	AY = 5380	AY = 2690	AY = 4035	AY = 5380
	kg ha⁻¹								
2801	58	78	86	78	88	91	86	91	91
2802	3	10	15	10	18	23	15	23	23
2803	0.9	3	6	3	8	11	6	11	10
2804	0	0	0	0	0	0	0	0	0
2805	0.5	2	4	2	5	8	4	8	7
2806	2	6	10	6	12	16	10	16	16
2807	35	57	68	57	72	78	68	78	77
2808	1	3	5	3	7	9	5	9	9
2809	69	86	91	86	93	95	91	95	95
2901	48	71	80	71	82	87	80	87	87
2902	8	20	29	20	33	40	29	40	39
2903	24	45	56	45	60	67	56	67	67
2904	54	75	83	75	86	90	83	90	89
2905	100	100	100	100	100	100	100	100	100
2906	82	93	96	93	97	98	96	98	98
2907	2	8	13	8	15	20	13	20	20
2908	35	58	69	58	72	78	69	78	78
2909	11	26	36	26	40	47	36	47	47
10111	39	62	72	62	75	81	72	81	80
10112	41	64	74	64	77	82	74	82	82
10113	41	64	74	64	77	82	74	82	82
10114	5	14	22	14	25	31	22	31	31
10115	5	14	21	14	24	31	21	31	30
10116	9	23	32	23	36	43	32	43	42
10117	39	62	72	62	75	81	72	81	81
10118	17	35	46	35	50	58	46	58	57
10119	97	99	100	99	100	100	100	100	100

†Environment represents the unique year and location combination. The numbers were used for coding a study site each year.

‡ST, seed treatment price; GSP, grain sale price; AY, actual yield.

respectively (Table 5). Dorrance et al. (2009) discussed several factors that needed to be considered for a response to seed treatments for *P. sojae*. In that paper, the best response occurred when conditions within the first 10 d after planting were wet. Also in that previous research, results from the trial in Wisconsin indicated no evidence of a response to the use of a seed treatment fungicide (Dorrance et al., 2009). A simple correlation of RR with rainfall in the first 10 d after planting in the current study indicated no association between these two variables. While there was some variation in planting dates over the years, locations were typically planted within a 2-wk period from the first week of May through approximately the third week of May. This may be enough time, however, to alter soil temperature and moisture conditions across environments, which may be one reason why responses were different. Also, during the course of this study, there were several fields in Wisconsin for which there was concern about a breakdown in resistance of the *Rps* 1k gene for *P. sojae* in soybean (Hughes et al., 2010). While results from the survey of problematic fields were not conclusive, this suggests that further work is needed to quantify the soil-borne pathogen profile in Wisconsin to improve recommendations regarding the use of seed treatments across environments.

When examining the two seed treatments separately, there was no evidence of a difference between the products (p = 0.1606). Individual tests for ApronMaxx and CruiserMaxx indicated that there was a positive response (1.5 and 2.9%, respectively) for both products and that both differed from 0 (p = 0.030 and < 0.0001, respectively) (Table 6). Economically, the probability of breaking even was affected by cost components (Table 6). For ApronMaxx, which has a lower treatment cost, the probability of breaking even was only less than 50% when grain sale price was lowest and actual yield was also low (Table 6). In the other eight comparisons, the probability of breaking even was >70%. For CruiserMaxx, a similar response was observed, although results indicated that a combination of higher grain sale price and actual yield were needed to offset the higher cost of the seed treatment (Table 6).

There was evidence that the response across environments and seed treatments differed by cultivar (p < 0.0001). Three cultivars, HS20R80 (+3.2%), KB177RR (+5.6%), and KB194RR (+5.7%), all had strong, positive response

Table 6. Probability of breaking even with the use of specific seed treatments across environments and cultivars.

Seed treatment	RR†	p	GSP‡ = US\$0.22 kg^{-1} AY = 2690	AY = 4035	AY = 5380	GSP = US\$0.33 kg^{-1} AY = 2690	AY = 4035	AY = 5380	GSP = US\$0.44 kg^{-1} AY = 2690	AY = 4035	AY = 5380
			kg ha^{-1}								
ApronMaxx§	1.5	0.030	42	72	84	72	87	92	84	92	94
CruiserMaxx	2.9	<0.001	3	56	88	56	93	100	88	98	98

†RR, relative response ratio, a comparison of yields with a seed treatment to the untreated check.

‡GSP, grain sale price; AY, actual yield.

§For each seed treatment, the respective seed treatment cost was used: US\$9.9 ha^{-1} for ApronMaxx and US\$24.7 ha^{-1} for CruiserMaxx.

ratios, meaning that seed yield was higher with a seed treatment compared to the UTC ($p < 0.001$) (Table 7). For these three cultivars, the corresponding probability of covering associated costs with the use of a seed treatment were typically >90% when the seed treatment was less expensive and >65% at the higher seed treatment price (Tables 7 and 8). For the other cultivars, the probability of breaking even was variable (Tables 7 and 8). For example, for AG1403 and P91Y90, the probability of breaking even was very low. For HS2025, with a lower seed treatment price, the probability of breaking even was >50% for all grain sale prices and actual yields when the seed treatment price was low. For P91Y70, a combination of lower seed treatment cost and higher grain sale price was needed to achieve the 50% benchmark, and for P91Y90, the probability of breaking even was low regardless of production situation.

There was no evidence of an overall effect of a cultivar and seed treatment interaction on the relative ratios (p = 0.4024); however, there were combinations where direct tests indicated significant positive or negative responses (Table 9). There were five combinations of cultivar and seed treatment where the positive response was significant at the 5% level (range: +3.6 to 7.7%), while there was one combination (AG1403–ApronMaxx) where the negative response (–3.2%) was significant (p = 0.014). For two cultivars (KB177RR and KB194RR), the probability of breaking even was high (>85%) across all combinations of seed treatment prices, grain sale prices, and actual yield. Results for the other cultivars varied considerably (Table 9). For example, HS2025 consistently covered the cost of the lower seed treatment price across grain sale prices and actual yields (probability of breaking even was >65%) but not necessarily for the higher seed treatment price. Cultivar HS20R80 had a similar response as HS2025 for the lower seed treatment price (probability of breaking even was >90%). For the higher seed treatment price, the probability of breaking even being greater than 50% was a function of either being in a high actual yield environment with low seed prices or having higher grain sale prices (Table 9). Interestingly, for P91Y70, the probability of breaking even being >50% was only found with CruiserMaxx and when grain sale prices were higher (\$0.33 or 0.44 kg^{-1}) and actual yield was higher. For AG1403 and P91Y90, the probability of breaking even was far less than 50%, regardless of seed treatment price and actual yield.

The complexity of the results regarding the probability of breaking even with the application of seed treatments suggests that making specific recommendations is difficult. Our results, though, were similar to observations made by Poag et al. (2005) who suggested that fungicide seed treatment decisions were appropriate across a range of locations and planting dates in Arkansas. There was some variation in planting date across years and locations in our trials that may have influenced potential response. Similar to the point raised by Poag et al. (2005), this may have been partly due to planting maturity groups outside their optimal dates. There was a positive response, on average, to the use of either seed treatment product (Table 5). Given that most growers do not have a clear understanding of specific issues affecting their fields (Conley et al., 2007; Conley and Santini, 2007) and industry-provided cultivar disease ratings are not always complete, recommendations

Table 7. Probability of breaking even with the application cost for a seed treatment fungicide (ApronMaxx) for individual cultivars across environments.

Soybean cultivar	RR†	p	ST‡ = US\$9.9 ha^{-1}; GSP = US\$0.22 kg^{-1} AY = 2690	AY = 4035	AY = 5380	ST = US\$9.9 ha^{-1}; GSP = US\$0.33 kg^{-1} AY = 2690	AY = 4035	AY = 5380	ST = US\$9.9 ha^{-1}; GSP = US\$0.44 kg^{-1} AY = 2690	AY = 4035	AY = 5380
			kg ha^{-1}			kg ha^{-1}			kg ha^{-1}		
AG1403	–1.3	0.138	0	0.3	0.8	0.3	1	2	1	2	3
HS2025	2.0	0.257	58	69	75	69	76	79	78	79	82
HS20R80	3.2	0.007	91	96	98	96	98	99	98	99	99
KB177RR	5.6	<0.001	100	100	100	100	100	100	100	100	100
KB194RR	5.7	<0.001	100	100	100	100	100	100	100	100	100
P91Y70	0.9	0.638	33	44	51	44	53	57	54	57	60
P91Y90	–0.7	0.716	10	17	21	17	22	25	23	25	28

†RR, relative response ratio, a comparison of yields with a seed treatment to the untreated check.

‡ST, seed treatment price; GSP, grain sale price; AY, actual yield.

Table 8. Probability of breaking even with the application cost for a seed treatment fungicide + insecticide (CruiserMaxx) for individual cultivars across environments.

Soybean cultivar	ST† = US$24.7 ha^{-1}; GSP = US$0.22 kg^{-1}			ST = US$24.7 ha^{-1}; GSP = US$0.33 kg^{-1}			ST = US$24.7 ha^{-1}; GSP = US$0.44 kg^{-1}		
	AY = 2690	AY = 4035	AY = 5380	AY = 2690	AY = 4035	AY = 5380	AY = 2690	AY = 4035	AY = 5380
		kg ha^{-1}			kg ha^{-1}			kg ha^{-1}	
AG1403	0	0	0	0	0	0	0	0	0.1
HS2025	11	33	48	33	54	64	48	64	63
HS20R80	21	65	83	65	88	94	83	94	94
KB177RR	88	99	100	99	100	100	100	100	100
KB194RR	91	99	100	99	100	100	100	100	100
P91Y70	4	15	25	15	29	39	25	39	38
P91Y90	0.4	3	7	3	8	13	7	13	13

†ST, seed treatment price; GSP, grain sale price; AY, actual yield.

based solely on cultivar many not be sufficient to making a seed treatment decision. Our multifaceted approach that integrates yield along with probability of break even points across different cost structures can provide a framework to growers for making seed treatment decisions.

CONCLUSIONS

Results from this study indicated that seed treatments can be a cost effective component of soybean production although several factors must be considered, in particular environment and cultivar. Although results suggested that yield response is driven by an interaction with cultivar, given the rapid turnover of cultivars and incomplete knowledge of reaction against early-season root rotting pathogens or soybean insects among other agronomic characteristics of interest, indicates that other factors will drive the probable use of seed treatments. There was not necessarily a consistent pattern of response by environment in these trials, indicating that further work is needed to elucidate specific factors that drive response. Ultimately, the development of a risk matrix may optimize the probability that the use of seed treatments will greatly improve producers' ability to make sound economic decisions to maximize profit.

Acknowledgments

The authors wish to thank the Wisconsin Soybean Marketing Board and the University of Wisconsin, College of Agricultural and Life Sciences for funding this research. We especially would like to thank Mark Martinka, John Gaska, and all members of the Conley and Esker programs for technical support. We also appreciate the comments and suggestions on an earlier version of this manuscript from Dr. Seth Naeve, Dr. Jill Miller-Garvin, Scott Rowntree, and David Marburger.

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Table 9. Relative response ratio and probability of breaking even with the application of a specific seed treatment by cultivar across environments.

Soybean cultivar	Seed treatment	RR†	*p*	GSP‡ = US$0.22 kg^{-1}			GSP = US$0.33 kg^{-1}			GSP = US$0.44 kg^{-1}		
				AY = 2690	AY = 4035	AY = 5380	AY = 2690	AY = 4035	AY = 5380	AY = 2690	AY = 4035	AY = 5380
					kg ha^{-1}			kg ha^{-1}			kg ha^{-1}	
AG1403	ApronMaxx§	–3.2	0.014	0	0	0	0	0.1	0.2	0	0.2	0.3
	CruiserMaxx	0.5	0.702	0.2	4	10	4	14	24	10	24	23
HS2025	ApronMaxx	2.7	0.254	67	75	78	75	80	82	78	82	83
	CruiserMaxx	1.3	0.571	11	27	37	27	41	49	37	49	48
HS20R80	ApronMaxx	4.1	0.012	93	97	98	97	98	98	98	98	99
	CruiserMaxx	2.4	0.139	13	40	57	40	63	73	57	73	72
KB177RR	ApronMaxx	3.6	0.030	88	93	95	93	96	97	95	97	97
	CruiserMaxx	7.7	<0.001	98	100	100	100	100	100	100	100	100
KB194RR	ApronMaxx	4.4	0.007	95	98	99	98	99	99	99	99	99
	CruiserMaxx	7.1	<0.001	96	100	100	100	100	100	100	100	100
P91Y70	ApronMaxx	0.07	0.978	25	33	37	33	39	42	37	42	44
	CruiserMaxx	1.7	0.491	15	32	43	32	47	54	43	54	54
P91Y90	ApronMaxx	–1.0	0.689	14	19	23	19	24	26	23	26	28
	CruiserMaxx	–0.4	0.877	3	9	15	9	18	23	15	23	23

†RR, relative response ratio, a comparison of yields with a seed treatment to the untreated check.

‡GSP, grain sale price; AY, actual yield.

§For each seed treatment, the respective seed treatment cost was used: US$9.9 ha^{-1} for ApronMaxx and US$24.7 ha^{-1} for CruiserMaxx.

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