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Fungicide, insecticide, and foliar fertilizer effect on soybean yield, seed composition, and canopy retention

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Abstract

Soybean [*Glycine max* (L.) Merr.] yield has increased over time through the introduction of new varieties and improved agronomic practices. However, seed protein concentration has decreased. We conducted field studies in 2018 and 2019 to investigate the effects of fungicide, insecticide, and foliar fertilizer application on grain yield and seed quality in two soybean maturity groups (MG). In-season treatments targeted nutrient availability and soybean canopy duration during the seed-filling period by fungicide, insecticide, or foliar fertilizer application at the onset of this period. Biomass samples were collected at R5, R6, and R7 and partitioned into plant parts. Year, location, and MG often influenced yield and seed composition, but foliar fungicide, insecticide, or fertilizer application had no impact on these parameters.

1 | INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] was produced and harvested on nearly 36 million ha in 2018 in the United States (USDA-NASS, 2019). Over the last century, soybean yields increased by 23.4 kg^{-1} ha^{-1} yr^{-1} but also displayed a slow dilution of soybean seed protein concentration (Rowntree et al., 2013). Current soybean grain pricing is based on yield and grain grading quality, which does not include seed oil or protein levels, or amino acid composition. Conversely, seed protein concentration is a factor for small grain prices, such as for wheat (*Triticum aestivum* L.; Kaur et al., 2017; Weidenbenner et al., 2014). Many wheat producers receive grain price deductions if they do not meet protein requirements. Nonetheless, lower soybean protein concentrations often affect meal processors trying to meet quality standards, and also impact farmers who feed soybean meal to livestock. Factors that influence seed protein concentration are grouped into three main categories: genetics (G), environment (E), and management (M), or G × E × M. The G × E × M interaction determines final soybean yield and protein concentration.

Knowing which varieties are less susceptible to pathogens or certain pests at variety selection can help maintain foliar canopies through the growing season. The environment plays a key role in seed quality and development through weather-related events. High air temperatures and moderate to low amounts of rainfall during the seed-fill period and during reproductive growth generally result in higher protein concentration in soybean seeds (Rotundo & Westgate, 2009). The magnitude of the increase in protein synthesis level depends on the timing and extent of the environmental stress. Seed mass can also be heavily influenced by environmental factors such as water availability and pest pressure. During seed fill these stresses will increase protein concentration (Naeve & Huerd, 2008). This increase in protein could be due to decrease in seed size and could be why protein is not normally correlated with higher yield (Rotundo & Westgate, 2009).

Abbreviations: MG, maturity group; R3, beginning pod; R5, beginning seed fill; R6, seed fill; R7, beginning maturity; SERF, South East Research Farm, Beresford, SD.

Seeds at lower parts of the plant tend to have higher amounts of oil, whereas the upper parts of the plant have more protein because the accumulation of oil in seeds often starts earlier in seed development than protein (Huber et al., 2016; Saldivar, Wang, Chen, & Hou, 2011). Along with temperature and water stress, other weather events (such as hail) can remove or damage leaves and thus have an impact on photosynthesis and protein synthesis. Hail damage can also lead to foliar disease development later in the growing season. Foliar diseases can reduce seed mass when not treated (Weidenbenner et al., 2014). Disease management via fungicide applications can help reduce soybean pathogens during the season.

Though a producer has minimal control over the weather conditions during the seed-fill period, there is some ability to influence the timing and length of the seed-fill period through the choice of the maturity length of the variety planted. Finding the right maturity group (MG) for the area is key to reaching full yield potential and maintaining seed quality. In addition to variety selection, planting date can also slightly influence the seed-filling period.

Protecting the plant canopy through management practices (e.g., supplying nutrient, or protection against pests) can prolong the beginning of leaf senescence. By delaying leaf senescence and maintaining photosynthesis, soybean plants will have a longer time to produce carbohydrate and protein in the seeds (Garcia & Hanway, 1976). Protein development starts later than oil synthesis and by extending time to physiological maturity will help increase protein concentrations in the seeds (Huber et al., 2016, Saldivar et al., 2011). Management practices are potentially the easiest way to increase yield and maintain the percentage of protein in the seed.

Foliar applications applied in-season can help maintain canopies. Foliar diseases or insects can reduce leaf area, which will lower photosynthesis and reduce yield (Bassanezi, Amorim, Filho, Hau, & Berger, 2001). Fungicide and insecticide applications can aid in maintaining healthy crop canopies during the seed-fill period, which relieves crop stress and extends photosynthetic production. Fungicides are often marketed as the “cure all” for soybean diseases but have been shown to mainly benefit fields that have a disease present (Jordan, 2010). Wrather and Koenning (2006) found that foliar diseases accounted for only about 7% of total yield reduction over the 3-yr period of their study. Other research has shown that fungicide applications are profitable even when disease problems are not present (Orlowski et al., 2016). However, following the integrated pest management principles, fungicide application should only be used when there are known or anticipated disease problems.

Another way to help maintain healthy canopies is by preventing nutrient deficiencies. Foliar fertilizers sometimes contribute to observed yield differences (Jordan, 2010). These nutrient deficiencies could be from lack of fertilization before planting, not supplying adequate amount of the nutrient that the crop needs or plants not being able to acquire it from the soil. Garcia & Hanway (1976) speculated that minimizing the nutrient depletion of soybean leaves caused by remobilization was the cause of yield increases from foliar fertilization. They hypothesized that this reduction in nutrient depletion delayed senescence of the soybean and extended the leaf photosynthetic activity and improved seed fill.

Core Ideas

- Yield did not improve with use of crop protection in low pest pressure environments.
- Seed composition did not improve in low pest pressure conditions.
- Reproductive biomass partitioning did not change with foliar protection applications.
- Slight improvement in leaf retention was seen with R3 fungicide and insecticide applications.

The objective of this research was to determine the effects of foliar insecticide, fungicide, and fertilizer applications at the beginning of seed filling on biomass accumulation and partitioning during the late seed-filling period, on grain yield and protein levels in soybean seeds in different MG varieties.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

This study was conducted in the eastern part of South Dakota at two of the South Dakota State University Research Farms; near Brookings, SD (44.3114˚ N, 96.7984˚ W), and near Beresford, SD (SERF; 43.0805˚ N, 96.7737˚ W). The soil types were Divide (fine-loamy over sandy, mixed superactive, frigid Aeric Calciaquolls), and Egan–Wentworth complex (fine-silty, mixed superactive, mesic Udic Haplustolls) at Brookings, and Egan–Clarno–Tetonka complex (fine-loamy/fine-silty, mixed superactive, mesic Typic Haplustolls) and Egan–Clarno–Trent complex (fine-silty, mixed superactive, mesic Udic Haplustolls) at SERF in 2018 and 2019, respectively.

Two soybean varieties, GH1024X and GH2041X (MG 1.0 and 2.0, respectively, Golden Harvest Seed), were planted in this study to vary seed-filling timing and duration. Six different foliar application treatments were applied on each variety at R3 (beginning pod) growth stage: untreated control, fungicide only, insecticide only, foliar fertilizer only, fungicide plus insecticide, and a combination of fungicide,

TABLE 1 Experimental design, varieties used, and other crop production parameters, along with planting, treatment application, biomass, and machine harvest dates

Field activities	2018 Brookings	SERF	2019 Brookings	SERF
Varieties	GH1024X, GH2041X			
Experimental design	RCBD			
Row spacing	0.76 m			
Replications	4			
Seeding rate	346,000 viable seeds ha^{-1}			
Plot dimensions	3 by 18.3 m	4.5 by 13.7 m		
Tillage	Conventional	No-till	Conventional	
Rotation	Corn–soybean	Oat–soybean	Corn–soybean	
Planting date	15 May[a]	17 May	2 June	8 June
R3 application	21 July	20 July	25 July	25 July
R5 Biomass	9 Aug.	6 Aug.	13 Aug.	15 Aug.
	13 Aug.		20 Aug.	19 Aug.
R6 Biomass	30 Aug.	20 Aug.	4 Sept.	3 Sept.
	7 Sept.	23 Aug.	10 Sept.	5 Sept.
R7 Biomass	14 Sept.	5 Sept.	23 Sept.	23 Sept.
	19 Sept.	12 Sept.	4 Oct.	30 Sept.
Machine harvest	19 Oct.	18 Oct.	19–20 Oct.	18 Oct.

Note. R3, beginning pod; R5, beginning seed fill; R6, seed fill; R7, beginning maturity; RCBD, randomized complete block design; SERF, South East Research Farm.
[a]Multiple dates for a field activity indicate that the MG1 and MG2 varieties have been sampled on separately on the days presented.

insecticide, and foliar fertilizer. The combination of variety and foliar product treatments were arranged in a randomized complete block design. This study only included the fungicide plus insecticide two-way interaction as these two types of chemicals are often applied together to protect soybean canopy from diseases and pests, and to manage the study size. Plots received the following products according to treatment assignment: Trivapro (*N*-[9-(dichloromethylene)-1,2,3,4-tetrahydro-1,4-methanonaphthalen-5-yl]-3-(difluoromethyl)-1-methyl-1*H*-pyrazole-4-Carboxamide, Methyl (E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate, 1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1*H*-1,2,4-triazole) fungicide at 0.172 L ha^{-1}; and Miravis (1*H*-Pyrazole-4-carboxamide, 3-(difluoromethyl)-*N*-methoxy-1-methyl-*N*-[1-methyl-2-(2,4,6-trichlorophenyl)ethyl]) fungicide at 0.172 L ha^{-1}; Endigo (1a(S*),3a(Z)]-cyano(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate, 3-(2-chloro-1,3-thiazol-5-ylmethyl)-5-methyl-1,3,5-oxadiazinan-4-ylidene(nitro)amine) insecticide at 0.052 L ha^{-1}, and Generate (0–0–0–0.28Fe–0.11Mn–0.14Cu–0.11Zn–0.001Mo–0.52Co–0.11Na) foliar fertilizer at 0.366 L ha^{-1} rates when sprayed at 140 L ha^{-1}.

Corn (*Zea mays* L.) was the preceding crop at both locations in 2019 and at the Brookings site in 2018. These sites utilized conventional tillage practices and fields were field cultivated a few days prior to planting, whereas at Beresford in 2018 soybean was planted in no-till ground following oat (*Avena sativa* L.). In 2019, soybean at the SERF site required replanting due to very poor plant stand caused by wet weather conditions during the planting and emergence window. Soybean varieties were planted at 346,000 seeds ha^{-1} in 76-cm rows (Table 1). Plots were maintained weed free. Plots sizes were 3 by 18.3 m in Brookings in 2018 and 4.5 by 13.7 m at SERF in 2018 and at both locations in 2019.

Foliar treatments were applied at the R3 growth stage in end of July 2018 and 2019 (Table 1). At the SERF site in 2018, planting error resulted in the foliar fertilizer treatment and the combination of the foliar fertilizer, fungicide, and insecticide being applied to the same MG soybean (e.g., foliar fertilizer was only applied to MG1, whereas the combination of the chemicals was applied only to MG2). This error was noticed at the beginning of leaf senescence.

2.2 | Field data collection

Before planting, soil samples were taken from each replication (15 cores with a 2-cm diameter soil probe) and separated to 0–15 cm and 15–60 cm; soil samples were air-dried with forced air then ground to pass through a 2-mm sieve, and sent off to a certified commercial laboratory (AgSource Laboratories) to determine soil nutrient concentrations, soil pH, and organic matter (OM). The laboratory used the 1:1 soil/water slurry method for soil pH; the loss of ignition method for OM; the cadmium reduction method for NO_3^-–N; the Bray-1 extraction method for P; the ammonium acetate extraction for K, Mg, and Ca; the monocalcium phosphate method for SO_4^{2-}–S concentration determination; the DTPA extraction method for Zn, Cu, Fe, and Mn; and the hot water extraction method for B (AgSource Laboratories, 2020).

Visual plant damage ratings were taken before foliar treatment application, 14 and 28 d after application for extent of leaf damage and presence and extent of disease based on percentage of leaf damage and percentage of the plant they made up in all site-years.

At approximately the V3 growth stage and at physiological maturity we estimated the plant population by conducting stand counts on 1-m lengths in the center two rows of each plot. Four counts were completed in each plot. At R5 (beginning seed), R6 (full seed), and R7 (beginning maturity) growth stages biomass samples were taken from a 0.5-m section of a non-border row; the sampling dates are presented in Table 1. The R5 and R6 samples were partitioned into leaves, stems, branches (including petioles), pods, and fallen leaves. The R7 samples were partitioned into leaves, stems, branches (including petioles), pod shells, seeds, and fallen leaves. Fallen leaves were any leaves and petioles that fell in the area where biomass was collected (0.38 m from each side of the row). All samples were dried at 60 °C until constant weight and the dry biomass accumulation was calculated.

The middle two rows were harvested with a Massey Ferguson 8XP plot combine in late October (Table 1). Seed weight and moisture readings were recorded. Plot lengths were measured to determine grain yield. Seed protein and oil concentrations were determined with InfraTec Nova instrument (FOSS Analytics) instrument. Seed mass (200-seed weight) was estimated by weighing grain samples collected from the harvested plots. Grain yield, seed protein and oil concentration, and the 200 seed weight data was adjusted to 130 g kg^{-1} moisture content.

2.3 | Statistical analysis

Results were analyzed in R Studio using analysis of variance (ANOVA) and Fishers' protected LSD at .05 significance level. The foliar application treatments, MG, year, and location were all considered fixed factors in the statistical model. The SERF site in 2018 was analyzed separately from the other three site-years due to the planting and foliar application error. The other three site-years were combined for statistical analysis.

3 | RESULTS AND DISCUSSION

3.1 | Site characteristics

Daily minimum and maximum temperatures, and precipitation in 2018 and 2019 for each site are shown in Supplemental Figure S1, and monthly mean, minimum, and maximum temperatures and monthly precipitation are presented in Supplemental Table S1. Air temperature followed closely, within ±1.5 °C of the 30-yr normal on the monthly average in each site, whereas daily observations were within ±5 °C of the daily 30-yr normal values. In general, air temperatures were slightly warmer than the 30-yr normal. However, an above normal precipitation pattern occurred in both years, especially in the early part of the growing season.

Soil pH, OM, and nutrient levels were not limited compared with the *South Dakota Fertilizer Recommendations Guide* (South Dakota State University, 2019) as shown in Table 2. There were no statistical differences in either early or late-season plant stands between the foliar application treatments, but there were some seasonal (site-year) differences (Supplemental Table S2; Tables 3 and 4). However, these differences in plant stands were not considered to impact yields.

3.2 | Biomass accumulation and partitioning

Weight of biomass partitions did not differ among treatments at any growth stage across the three site-years (Supplemental Table S3). Likewise, plant parts biomass accumulation did not differ statistically among the foliar application treatments at the R5 growth stage, but the year × location interaction was statistically significant (Supplemental Table S3). Biomass accumulation in 2019 was lower than in 2018 by ~1,000 kg ha^{-1} at both locations at all three growth stages (Figure 1). Foliar application treatments did not influence the amount of biomass that the plant maintained through the late reproductive (R5–R7) stages except for the leaf biomass at the R6 growth stage, and the leaves and pods biomass weight differed at the R7 growth stage (Supplemental Table S3 and Table 5). Foliar fertilizer treatment alone resulted about 250 kg ha^{-1} lower leaf biomass production compared with the combination of fungicide, insecticide, and foliar fertilizer application at the R6 growth stage whereas the other foliar application treatments did not differ (Table 5). The fungicide only or treatment combinations containing fungicide produced the three largest leaf biomass at the R7 growth stage averaged across MGs and site-years (Table 5). Only the fungicide and insecticide treatment did not differ from the other three non-fungicide containing treatments. This observation agrees with Parker and Boswell (1980) findings where they noticed delayed senescence after fungicide applications.

TABLE 2 Pre-plant soil test levels for pH, organic matter, and nitrate-N, P, K, S, Ca, Mg, Zn, Mn, Cu, Fe, and B nutrients

	2018				2019			
	Brookings		SERF		Brookings		SERF	
Soil parameter[a]	0–15 cm	15–60 cm	0–15 cm	15–60 cm	0–15 cm	15–60 cm	0–15 cm	15–60 cm
pH	6.6 ± 0.4	7.6 ± 0.4	6.3 ± 0.9	6.9 ± 0.7	5.7 ± 0.2	6.5 ± 0.1	6.2 ± 0.2	7.6 ± 0.5
OM, %	4.5 ± 0.4	2.7 ± 0.1	3.4 ± 0.5	3.0 ± 0.5	3.3 ± 0.3	2.8 ± 0.2	3.2 ± 0	2.6 ± 0.2
Nitrate-N, mg kg^{-1}	22.5 ± 7.5	8.0 ± 3.2	4.0 ± 2.6	5.3 ± 1.3	2.5 ± 0.6	2.7 ± 0.5	2.6 ± 0.2	1.0 ± 0.5
P, mg kg^{-1}	40.3 ± 8.5	5.5 ± 2.5	19.8 ± 12.5	8.8 ± 8.5	19.5 ± 21.9	18.8 ± 11.1	25.2 ±1.8	7.1 ± 1.0
K, mg kg^{-1}	272 ± 62	119 ± 25	231 ± 66	186 ± 82	369 ± 171	210 ± 84	304 ± 24	117 ± 4
Sulfate-S, mg kg^{-1}	11.3 ± 1.0	8.8 ± 0.5	7.0 ± 4.0	7.5 ± 2.5	3.0 ± 0	2.0 ± 0.	5.0 ± 1.4	5.3 ± 1.5
Ca, mg kg^{-1}	3238 ± 360.	4361 ± 219	3036 ± 1686	2878 ± 88	2670 ± 957	2970 ± 512	2230 ± 208	2747 ± 592
Mg, mg kg^{-1}	739 ± 147	767 ± 32	718 ± 267	899 ± 255	594 ± 124	844 ± 276	571 ± 42	703 ± 84
Zn, mg kg^{-1}	2 ± 0.4	0.3 ± 0.2	0.8 ± 0.6	0.5 ± 0.3	1.3 ± 0.5	1.0 ± 0.5	1.3 ± 0.1	0.8 ± 0.6
Mn, mg kg^{-1}	29 ± 11.4	6 ± 0.6	47 ± 21.6	31.0 ± 29.4	25.5 ± 16.0	14.56 ± 5.3	62.2 ± 13.4	16.2 ± 8.6
Cu, mg kg^{-1}	16 ± 0.2	1.1 ± 0.4	1.5 ± 0.3	1.5 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.6 ± 0.1	1.5 ± 0.4
Fe, mg kg^{-1}	33 ± 10.4	15 ± 2.2	68 ± 32.5	38.2 ± 30.4	50.8 ± 27.7	26.9 ± 15.5	71.8 ± 3.3	18.7 ± 3.0
B, mg kg^{-1}	0.5 ± 0.1	0.6 ± 0.1	0.4 ± 0.1	0.5 ± 0.2	0.5 ± 0.1	0.7 ± 0.3	0.4 ± 0.1	0.7 ± 0.2

Note. OM, organic matter; SERF, South East Research Farm.

[a]Soil parameter values were determined by the following analytical methods: pH, 1:1 soil/water slurry method; OM, loss of ignition method; NO_3–N, cadmium reduction method; P, Bray-1 extraction method; K, Ca, Mg, ammonium acetate extraction; SO_4^{2-}–S, monocalcium phosphate method; Zn, Cu, Fe, and Mn, DTPA extraction method; B, hot water extraction method (AgSource Laboratories, 2020).

TABLE 3 Main treatment effect on early season and final plant stands, grain yield, and seed protein and oil concentrations in 2018 and 2019 near Brookings and Beresford, SD

Treatment (combinations)	Early season	Final stand	Grain yield	Seed protein conc.	Seed oil conc.
	plants ha^{-1}		Mg ha^{-1}	%	
Foliar application treatment					
Control	270,600	245,900	3.95	35.2	17.9
Fungicide	266,400	240,900	4.07	35.2	17.9
Insecticide	268,100	243,100	4.04	35.0	18.0
Fungicide and insecticide	266,600	240,700	4.02	35.0	18.1
Foliar fertilizer	266,900	251,100	4.02	35.1	18.0
FFI	278,700	242,700	4.03	35.1	18.0
Maturity group					
MG1	273,800a[a]	250,100a	3.80b	35.3	17.8b
MG2	265,100b	237,700b	4.24a	35.2	18.1a
Year × location					
2018 Brookings	275,300a	196, 207c	4.51a	36.5a	17.9b
2019 Brookings	274,200a	272,500a	3.59b	34.6b	17.8b
2019 SERF	253,300b	254,500b	3.94ab	34.7b	18.1a

Note. FFI, combination of foliar fertilizer, fungicides, and insecticide application; MG, maturity group; ; SERF, South East Research Farm.

[a]Different lower-case letters indicate statistically different results within a column at $p = .05$ confidence level.

TABLE 4 Fungicide, insecticide, and foliar fertilizer application effect on stand counts, grain yield, seed protein, and oil concentrations in Beresford, SD, in 2018

Maturity group	Foliar application treatment	Early stand	Final stand	Grain yield	Seed protein	Seed oil
		plants ha^{-1}		Mg ha^{-1}	%	
MG1	Control	247,200	220,200	5.53	35.1 bc[a]	18.5
	Fungicide	252,600	231,800	5.62	34.7 c	18.7
	Insecticide	260,000	241,700	5.51	34.9 c	18.4
	Fungicide and insecticide	251,000	238,400	5.64	34.9 c	18.5
MG2	Control	244,400	233,800	5.52	35.0 bc	18.7
	Fungicide	236,200	241,700	5.91	35.2 ab	18.9
	Insecticide	251,800	246,100	5.71	35.0 bc	18.8
	Fungicide and insecticide	254,300	235,100	5.93	35.5 a	18.7
		p* < *F				
	MG	.98	.01	.05	<.0001	<.0001
	Treatment	.92	.33	.003	.10	.01
	MG × treatment	.85	.88	.55	.04	.14

[a]Different lower-case letters indicate statistically different results within a column at $p = .05$ confidence level.

Samples at the R5 growth stage were collected on the same day across MG (Table 1), which also contributed to the differences between the varieties. However, at later growth stages sample collection was targeting the time when MGs reached the target growth stage. Due to the large number of plots to sample during the grain-filling period the sample collection still occurred at slightly different sub-developmental stages across MGs (e.g., MG1 samples were collected at R5.3 and MG2 samples were collected at R5.1), which might account for some differences seen between MGs (Table 6) and consequently contributed to the nonsignificant statistical differences among the foliar application treatments. The growing season (site-years) also influenced the biomass accumulation in the individual plant parts as shown in Table 6. However, the relative plant partitions (e.g., percentage of the total biomass accumulation for a plant partition) did not differ among treatments (data not shown).

Both growing seasons were wetter than the 30-yr average, which influenced the emergence and stand uniformity, even though the average plant population did not differ substantially among the foliar application treatments (Tables 3 and 4). However, plant stand heterogeneity may vary the number of plants collected in a sample (plants were cut from a 0.5-m section of the row) and potentially impact total biomass accumulation and more likely the partitioning of the biomass. Overall, the foliar fungicide application produced only a minimal effect, influencing the biomass partitioning (Table 5).

3.3 | Disease and pest damage assessment

There were seasonal differences in pest damage ratings prior to the foliar application when comparing 2018 and 2019 (Supplemental Table S4). In 2018, initial insect damage ratings indicated increased leaf damage prior to the R3 foliar application than was observed in 2019. The disease pressure prior to the foliar protection application were similar between the 2 yr (Supplemental Table S4). Following foliar insecticide, fungicide, or foliar fertilizer application, higher insect damage was observed in the untreated control and the foliar fertilizer only treatments in the pest damage assessment timing and foliar application treatment interactions (Supplemental Table S5). However, no noticeable disease pressure differences were observed 14 and 28 d after application (Supplemental Table S4 and Supplemental Table S5).

3.4 | Grain yield, seed protein, and oil concentrations

The growing season × location interaction influenced both grain yield, seed protein, and oil concentrations

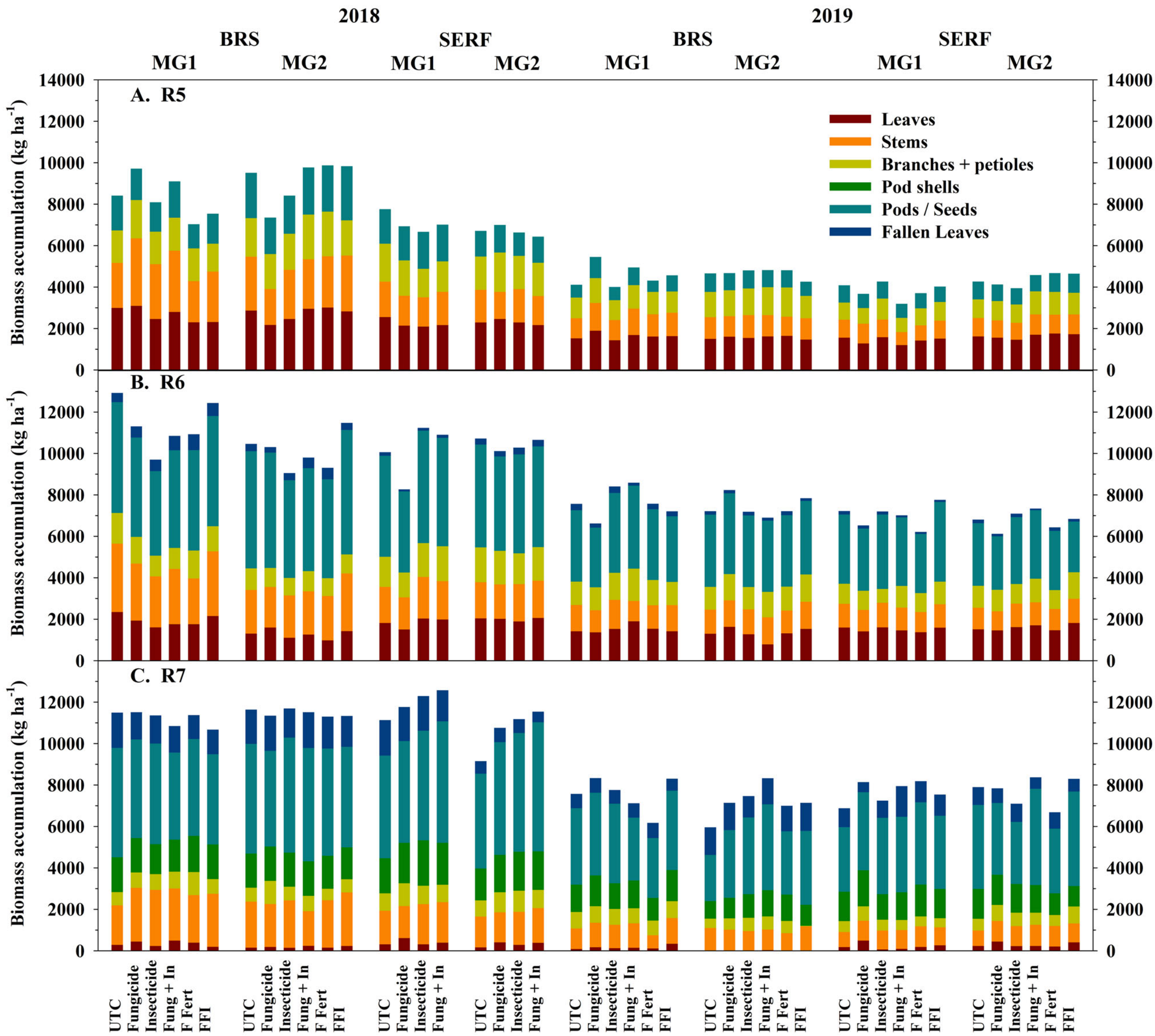

FIGURE 1 Fungicide, insecticide, and foliar fertilizer application effects on R5, R6, and R7 biomass accumulation and partitioning in eastern South Dakota in 2018 and 2019

(Supplemental Table S2). However, only grain yield and seed oil concentration differed due to the varieties, and to the year × location × MG interaction (Supplemental Table S2). The foliar application treatments alone did not lead to yield, seed protein, or oil concentration differences averaged across growing season, locations, and varieties (Supplemental Table S2). Data on yield, seed protein, and oil concentrations are shown in Tables 3 and 4. The MG2 variety out-yielded the MG1 variety by about 0.45 Mg ha^{-1} averaged across the foliar application treatments and site-years (Table 3). Seed oil concentration was also numerically higher with fungicide and insecticide treatment compared with the other foliar application treatments averaged across the MGs and site-years. At Brookings, the MG1 variety had approximately from 0.4 to 0.8% higher seed protein concentration than the other MGs in the location × MG interaction, whereas all other MG varieties in Brookings and SERF had approximately 0.4% higher grain oil concentration (Table 7).

The highest yield was achieved in 2018 at the Brookings site with the MG2 variety compared with all the other treatments in the year × location × MG interaction (Table 7). Seed protein concentration was the highest in the MG1 variety at Brookings across the foliar treatment applications and for the seed oil concentration was the opposite, with the MG1 variety at the Brookings site being the lowest (Table 7). At the Brookings sites the MGs differed both in seed protein and oil concentrations, whereas at the SERF site the MGs had similar seed composition.

The SERF site in 2018 that was analyzed separately (Table 4); the fungicide only and the fungicide and

TABLE 5 Fungicide, insecticide, and foliar fertilizer application, effect on R5, R6, and R7 biomass dry matter by plant fractions (leaves, main stem, branches and petioles, and pods) in eastern South Dakota in 2018 and 2019

Foliar treatments	Leaves	Main stem	Branches + petioles	Pods; seeds/pod shells	Total biomass
	kg ha^{-1}				
			R5		
Control	2,051	1,606	1,343	2,047	7,047
Fungicide	2,020	1,444	1,396	1,852	6,712
Insecticide	2,031	1,477	1,435	2,095	7,038
Fungicide and insecticide	2,045	1,528	1,387	2,156	7,116
Foliar fertilizer	1,963	1,331	1,352	1,678	6,324
FFI	1,969	1,519	1,237	1,770	6,495
			R6		
Control	1,657ab[a]	1,697	1254	4,287	8,895
Fungicide	1,629ab	1,519	1180	3,895	8,223
Insecticide	1,606ab	1,642	1213	4,123	8,584
Fungicide and insecticide	1,654ab	1,642	1241	4,192	8,729
Foliar fertilizer	1,482b	1,506	1123	3,876	7,987
FFI	1,720a	1,797	1248	4,258	9,023
			R7		
Control	206b	1,192	694[b]	4,431b	6,523
Fungicide	348a	1,236	800	4,737ab	7,121
Insecticide	203b	1,333	717	4,737ab	6,990
Fungicide and insecticide	284ab	1,237	715	5,026a	7,262
Foliar fertilizer	215b	1,297	645	4,916ab	7,073
FFI	325a	1,258	714	4,500b	6,797

Note. FFI, combination of foliar fertilizer, fungicides, and insecticide application; R5, beginning seed fill; R6, seed fill; R7, beginning maturity.

[a]Different lower-case letters indicate statistically different results within a column at $p = .05$ confidence level.

[b]Branches and petiole fractions at R7 growth stage contained mainly branches, as petioles have fallen.

TABLE 6 Maturity group main effect and year × location interaction on leaves, stems, branches and petioles, pods, seeds, pod shells, and total biomass at the various reproductive growth stages in 2018 and 2019

Treatment (combinations)	Location	Leaves	Stems	Branches	Pods; seeds/pod shells	Total
			Growth stage R5			
MG						
MG1		1,935b[a]	1,534a	1,306b	1,606a	6,382b
MG2		2,030a	1,529b	1,510a	1,599b	6,669a
Year × location						
2018	Brookings	2,603a	2,484a	1,727a	1,784b	8,598a
2019	Brookings	1,597b	1,196b	1,192b	5,057a	4,756b
	SERF	1,562b	847b	1,040b	789b	4,239b
			Growth stage R6			
MG						
MG1		1,842a	1,820a	1,435b	4,065a	9,471a
MG2		1,797b	1,690b	1,470a	4,012b	9,348b
Year × location						
2018	Brookings	2,244a	3,020a	1,785a	5,057a	12,601a
2019	Brookings	1,530b	1,282b	1,259b	3,287b	7,656b
	SERF	1,549b	940b	1,138b	3,157b	7,072b
			Growth stage R7			
MG						
MG1		297b	1,536a	750b	3,521b/1,653b	8,540b
MG2		328a	1,453b	827a	3,635a/1,725a	8,696a
Year × location						
2018	Brookings	458a	2,331a	848a	2,169b/792b	7,813b
2019	Brookings	126c	1,021b	632b	2,945b/2,311a	7,587b
	SERF	317b	962b	652b	4,354a/1,760a	8,024a

Note. MG, maturity group; R5, beginning seed fill; R6, seed fill; R7, beginning maturity; SERF, South East Research Farm.

[a]Different lower-case letters indicate statistically different results within a column at $p = .05$ confidence level.

TABLE 7 Year × location × maturity group (MG) interaction effect on grain yield, and location × MG interaction effect on seed protein and oil concentrations in 2018 and 2019 near Brookings, SD, and Beresford, SD (SERF)

Year/location	Maturity group	Grain yield	Seed protein conc.	Seed oil conc.
		Mg ha^{-1}	—%—	
Year × Location × MG				
2018 Brookings	MG1	4.4b[a]		
	MG2	4.8a		
2019 SERF	MG1	3.7c		
	MG2	4.2b		
2019 Brookings	MG1	3.4d		
	MG2	3.8c		
Location × MG				
Brookings	MG1		35.7a	17.6b
	MG2		35.3b	18.1a
SERF	MG1		34.5c	18.0a
	MG2		34.9bc	18.1a

Note. MG, maturity group; SERF, South East Research Farm.
[a]Different lower-case letters indicate statistically different results within a column at $p = .05$ confidence level.

insecticide combination out-yielded the untreated control plots (5.76, 5.78, and 5.51 Mg ha^{-1}, respectively) averaged across the MGs (Table 4). The MG2 variety produced higher yield, seed protein, and oil concentrations compared with the MG1 variety (Table 4).

Rotundo and Westgate (2009) found protein increases with drought stress during seed fill. None of our site-years had this type of water stress; the Brookings site in 2018 had the lowest amounts of precipitation during seed fill for the two growing seasons and also with higher levels of protein concentration than in 2019. At SERF in 2018, the trial had large amount of rainfall during seed fill and slightly warmer than normal weather throughout the season and ended up having the highest yield and protein concentration in this study.

The location effect on yield is related to environmental factors such as the higher early season precipitation and warmer temperatures (Naeve & Huerd, 2008) during the growing season similar to our SERF site. Previous research also found that fungicide applications did not improve yield in the absence of disease pressure (Swoboda & Pedersen, 2009). However, other research indicates a profitable response even without disease pressure (Orlowski et al., 2016), due to what is usually termed a *physiological effect*. In addition, Bandara et al. (2020) recently reported that farmers in low-yielding regions use fungicide with the goal of increasing yields, but without truly knowing or formally assessing the true effect. Our study did not show yield or protein response to the foliar fungicide, insecticide, or fertilizer applications in the absence of soybean stressors during the two growing seasons except for yield at the SERF site in 2018. Moreover, spraying fungicide and insecticide below the pest economical thresholds (e.g., not following the integrated pest management approach) increase input costs while reducing profitability, and may lead to resistance problems.

Further investigation in fields that have pest or disease presence would be important to find out if these foliar applications would benefit yield and seed composition more consistently. South Dakota has a problem with white mold in soybean. However, the R3 application timing was too late to prevent white mold infection, but the seed-filling period was the main focus of this study. Future studies could address the effect of different fungicide or insecticide application timings on seed quality and disease development and their interaction.

4 | CONCLUSION

The current study showed that foliar fungicide, insecticide, or fertilizer applications (or the combination of these treatments) at the beginning of the grain-fill period generally did not impact yield or seed protein except in one of four site-years. The lack of response to foliar fungicide, pesticide, and fertilizer application was attributed to low insect and disease pressure and adequate soil nutrient supply. Even though fungicide application, alone or in combination with other treatments, showed somewhat delayed leaf senescence, it did not affect overall biomass accumulation and partitioning or grain yield. Our results indicate no benefit to these foliar treatments at the beginning of pod setting (R3 growth stage) in the absence of disease, pest, or nutrient stress. Application of the fungicide, insecticide, or foliar fertilizer products without yield response will also lower profitability. Maturity group, and site-year interactions did influence seed protein and oil concentrations, which also highlights the importance of variety selection. Nonetheless, without market incentive for higher seed protein concentration our results indicate no justification to use these treatments in the absence of pest pressure.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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