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RESEARCH

Yield Response to Crop/Genotype Rotations and Fungicide Use to Manage *Fusarium*-related Diseases

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ABSTRACT

Corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] cropping systems of the Midwest have led to increased selection pressure on diseases caused by *Fusarium* pathogens. A field experiment was conducted from 2010 to 2012 near Arlington, WI, to identify interactions among disease management practices (crop rotation, host resistance, and fungicide use) that increase corn, soybean, and wheat (*Triticum aestivum* L.) yields. For corn grain, significant interactions were primarily driven by crop rotation. Highest corn yields across all 3 yr were observed in the corn–soybean–wheat (CSW) rotation (13.55 Mg ha^{-1}). Corn silage yield was influenced by cultivar rotation, with highest yields displayed by the *Fusarium*-susceptible rotations (susceptible followed by susceptible followed by susceptible [SSS] and susceptible followed by susceptible followed by resistant [SSR]). Soybean yields were influenced by interactions involving crop rotation and cultivar rotation. Highest soybean yields were found for crop rotations containing wheat and ranged from 5.1 to 8.4% higher than the corn alternated annually with soybean (CS) rotation. The *Fusarium*-resistant (resistant followed by resistant followed by resistant [RRR]) cultivar rotation (4.14 Mg ha^{-1}) yielded 3.0% better than the next highest rotation (SSR). Crop rotation, cultivar selection, and fungicide use were all key drivers for wheat yield. Highest yields on average were observed in the CSW rotation (5.62 Mg ha^{-1}). The *Fusarium* head blight (FHB)–susceptible cultivar (5.50 Mg ha^{-1}) yielded significantly higher compared to the resistant cultivar (4.89 Mg ha^{-1}), and fungicide use increased yield in the susceptible cultivar 7.2% (5.31 to 5.69 Mg ha^{-1}) but not for the resistant cultivar. Although interactions were not consistent for all three crops, our results suggest growers should begin with combining a high-yield-potential cultivar, regardless of its susceptibility or resistance to *Fusarium* pathogens, in a CSW crop rotation to maximize yield potential when managing *Fusarium*-related diseases.

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Abbreviations: CC, continuous corn; CS, corn alternated annually with soybean; CSW, corn followed by soybean followed by wheat; CWS, corn followed by wheat followed by soybean; C_sW_sS, corn followed by wheat followed by soybean in which corn was harvested as silage and wheat straw was removed where appropriate; FHB, *Fusarium* head blight; RRR, resistant followed by resistant followed by resistant; RRS, resistant followed by resistant followed by susceptible; SS, continuous soybean; SSR, susceptible followed by susceptible followed by resistant; SSS, susceptible followed by susceptible followed by susceptible; SDS, sudden death syndrome.

Using diverse crop rotations as a management tool for increasing yield potential has been recognized for centuries (Crookston et al., 1991). Diverse crop rotations were extremely important before the 1950s for control of yield-limiting factors such as weed competition, insect pests, and diseases. With the discovery and use of synthetic pesticides and fertilizers beginning in the 1950s and 1960s, diverse crop rotations were slowly replaced with corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] cropping systems throughout the Midwest, and in recent years, expanded adoption of corn–soybean cropping systems can be attributed to

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increased profitability due to increased commodity prices for both crops (USDA-ERS, 2014). The use of continuous corn and soybean and corn–soybean rotations continues to this day, with an estimate of the two crops together representing >80% of the arable land in many midwestern states (Hoeft et al., 2000).

Much research has evaluated the effect of corn–soybean cropping sequences on yield. Crop rotation has shown to increase corn yield from 5 to 30% and soybean yield from 8 to 20% compared to continuous production of either crop (Copeland et al., 1993; Crookston et al., 1991; Lund et al., 1993; Pedersen and Lauer, 2002, 2003; Stanger and Lauer, 2008). Adding wheat (*Triticum aestivum* L.) into corn–soybean cropping systems has not received as much attention. Dill-Macky and Jones (2000) found wheat following soybean yielded higher than wheat following corn; however, Lund et al. (1993) found no yield advantage for introducing wheat into a corn–soybean crop rotation. Although the cause for increased yields from using a crop rotation remains unknown, proposed reasons for higher yields include increased soil fertility, improved soil physical properties, improved weed control, and reduced disease and insect pressure (Wesley et al., 2001).

A lack of diverse cropping systems has also increased risk from certain pests within these systems, including diseases caused by *Fusarium* pathogens. For corn, soybean, and wheat producers throughout the United States, diseases caused by the pathogens *Fusarium virguliforme* and *Fusarium graminearum* have continued to spread and cause dramatic yield loss. Sudden death syndrome (SDS), caused by *F. virguliforme*, was discovered in Arkansas in 1971 (Hirrel, 1983), and while it is a relatively new disease to much of the soybean growing areas of the Midwest, this disease has spread to Kentucky, Missouri, Mississippi, Tennessee, Alabama, Georgia, Kansas, Ohio, Illinois, Indiana, Minnesota, and Wisconsin (Roy et al., 1989, 1997; Wrather and Koenning, 2009). The first report of SDS in Wisconsin occurred in 2006 (Bernstein et al., 2007), and survey efforts since then have shown *F. virguliforme* has spread to other regions of the state not originally described by Bernstein et al. (2007) (Marburger et al., 2013). Characteristics of high-yield environments coincide with conducive conditions for SDS development, leading to increased potential for significant yield loss. Sudden death syndrome ranked among the top ten of yield-suppressing diseases in the United States in 11 of 12 yr from 1996 to 2007. It often ranked second to fifth in those years (Wrather and Koenning, 2009). Yield loss up to 80% in individual fields has been attributed to SDS, but yield loss of 5 to 15% is more common.

In addition to the spread of SDS, *F. graminearum* is regarded as an economically important pathogen of wheat, where it causes *Fusarium* head blight (FHB), and in corn, where it causes ear and stalk rot (Broders et al., 2007). In wheat, yield losses of 30 to 70% can result when disease symptoms are severe (Bai and Shaner, 1994), and in corn, annual yield loss from *Gibberella* ear and stalk rot (i.e., the sexual stage of *F. graminearum*) has been estimated at 5 to 15% but can vary greatly between years and locations (Lipps et al., 2001). In addition, *F. graminearum* has been recently shown to be pathogenic on soybean, causing seed decay and damping off (Broders et al., 2007; Pioli et al., 2004).

To help minimize risk of disease development and potential yield loss, growers can use disease-resistant cultivars. Much research has been conducted for developing resistant cultivars to SDS, FHB, and *Gibberella* and *Fusarium* ear and stalk rot on corn (Ali et al., 2005; Bai and Shaner, 2004; Hershman et al., 1990; Munkvold et al., 1997; Rupe et al., 1991; Sciumbato and Keeling, 1985; Vick et al., 2006). Additionally, Ellis et al. (2012) recently identified five soybean genotypes with resistance to *F. graminearum* to aid in control; however, the extent of commercial cultivars with resistance to this pathogen is unknown. While choosing a cultivar with high yield potential is one of the most important management decisions a grower can make (Conley et al., 2010a), the effect on yield from rotating cultivars with susceptibility or resistance to *Fusarium*-related pathogens is not yet well known.

In addition to crop rotation and host resistance, fungicide use is another management tool for controlling diseases. For diseases caused by *Fusarium* pathogens, use of a fungicide seed treatment or foliar fungicide depends on the *Fusarium* species. Many studies have assessed the efficacy of foliar fungicides for controlling FHB on small grains, but results have been mixed (Cromey et al., 2001; Hollingsworth et al., 2006; Ioos et al., 2005; Jones, 2000; Mesterhazy et al., 2003; Milus and Parsons, 1994; Wegulo et al., 2011). Fungicide seed treatment studies have demonstrated efficacy on *Fusarium* spp., but the efficacy of different active ingredients varies with different *Fusarium* species (Broders et al., 2007; Ellis et al., 2011; Munkvold and O'Mara, 2002). While fungicides can be useful, positive yield responses from fungicide use are often year and location dependent (Bradley, 2008) and unlikely to be profitable when low disease pressure is observed in a high-yielding environment (Paul et al., 2011).

As less diverse cropping systems continue to be utilized, integrating multiple strategies for disease management will become more important for growers. Currently, there is limited information regarding how combinations of multiple management practices not only affect disease development from *Fusarium*-related pathogens but also subsequent yield. Identifying interactions among multiple management practices that reduce risk of disease development and maintain high yield potential would be useful information for growers as they develop long-term disease management plans.

To examine interactions among multiple disease management practices, a comprehensive study was designed and implemented to meet two objectives: (i) identify possible combinations of practices that could reduce risk of disease development by decreasing *Fusarium* spp. populations (Marburger et al., 2015); and (ii) quantify the effect of combinations of these practices on yield (current study). In an earlier study, Marburger et al. (2015) showed that there were few interactions among crop rotation, cultivar selection, and fungicide use that reduced soil populations of three *Fusarium* species, with significant interactions or individual control methods dependent on the species being examined. This paper will focus on the influence of crop rotation, cultivar rotation, and fungicide use on yield, with an emphasis of these management practices aimed at controlling diseases caused by *Fusarium* spp.

MATERIALS AND METHODS

Field research was conducted from 2010 to 2012 in a long-term corn–soybean–wheat rotation study at the University of Wisconsin-Madison Agricultural Research Station near Arlington, WI (43°18′ N, 89°20′ W) (Table 1). This study was established in 2002 on a Plano silt loam soil (fine-silty, mixed, mesic Typic Argiudoll) with a 2 to 6% slope, and no-tillage practices have been performed since establishment. The experimental design was a randomized complete block in a split-split-plot arrangement with three replications. The main plot factor consisted of the 14 crop rotation sequences, representing each phase of seven different crop rotations (Table 2), and main plots were 18.3 m wide and 18.3 m long. The subplot and sub-subplot treatments were established in 2010 as part of a 3-yr cycle. Subplot treatments consisted of two cultivars chosen based on their relative resistance (R) or susceptibility (S) to important *Fusarium* pathogens regarding each crop and were arranged in four rotations (susceptible followed by susceptible followed by susceptible [SSS], resistant followed by resistant followed by resistant [RRR], susceptible followed by susceptible followed by resistant [SSR], and resistant followed by resistant followed by susceptible [RRS]). Sub-subplots consisted of two fungicide treatments, use of a fungicide versus an untreated check. Fungicide use was different for each crop. Headline (pyraclostrobin {carbamic acid, [2-[[[1-(4-chlorophenyl)-1*H*-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-, methyl ester}) was applied to the corn at the V5 growth stage (Ritchie et al., 1992) at 439 mL ha^{-1}. Maxim seed treatment (fludioxonil [4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1*H*-pyrrole-3-carbonitrile] [0.0076 mg seed^{-1}]) was used for the soybean. Prosaro 421 SC (prothiconazole {2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1,2-dihydro-3*H*-1,2,4-triazole-3-thione} and tebuconazole {⟨-[2-(4-chlorophenyl)ethyl]-⟨-(1,1-dimethylethyl)-1*H*-1,2,4-triazole-1-ethanol}) was applied to the wheat at the Feekes 10.5.1 growth stage (Large, 1954) at 600 mL ha^{-1}. Sub-subplot experimental units were 3 m wide and 9 m long.

Plots were mechanically seeded to establish a target plant density (plants ha^{-1}) of 80,000 (corn), 371,000 (soybean), and 4,200,000 (wheat). Corn and soybean plots consisted of four rows spaced 76 cm apart, and wheat plots consisted of 16 rows spaced 19 cm apart. Cultivars used for each crop can be found

Table 1. Soil fertility, cultivars used, and dates of field operations for each crop during the 2010–2012 growing seasons.

Parameter	Year 2010	Year 2011	Year 2012
Soil fertility†			
Phosphorus (mg kg^{-1})	19	19	19
Potassium (mg kg^{-1})	127	102	104
pH	6.9	6.2	6.9
Organic matter (g kg^{-1})	31	32	29
Cultivars used			
Corn			
Susceptible (S)	Pioneer 37N16	Pioneer 37N16	Pioneer 0392AMX-R
Resistant (R)	Pioneer 37N68	Pioneer 37N68	Pioneer 9917AM1
Soybean			
Susceptible (S)	Pioneer 92M33	Pioneer 92M33	Pioneer 92M33
Resistant (R)	Pioneer 92Y30	Pioneer 92Y30	Pioneer 92Y30
Wheat			
Susceptible (S)	Pioneer 25R47	Pioneer 25R47	Pioneer 25R47
Resistant (R)	Excel 234	Excel 234	Excel 234
Field operations			
Corn			
Planting date	10 May	11 May	11 May
Harvest date			
Silage	2 Sept.	7 Sept.	4 Sept.
Grain	30 Sept.	12 Oct.	25 Sept.
Soybean			
Planting date	4 May	4 May	11 May
Harvest date	4 Oct.	6 Oct.	3 Oct.
Wheat			
Planting date	19 Oct. (2009)	10 Oct. (2010)	7 Oct. (2011)
Harvest date	19 July	26 July	2 July

† Plant-available phosphorus and potassium determined by Bray-P1 soil test.

Table 2. Crop rotation sequences for the corn (C), soybean (S), and wheat (W) rotations from 2002 to 2012.

	Crop rotation sequence†													
	Continuous			CS rotation		CSW rotation			CWS rotation			C_sW_sS rotation		
Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2012	C	S	W	C	S	S	W	C	W	S	C	W_s	S	C_s
2011	C	S	W	S	C	C	S	W	C	W	S	C_s	W_s	S
2010	C	S	W	C	S	W	C	S	S	C	W	S	C_s	W_s
2009	C	S	W	S	C	S	W	C	W	S	C	W_s	S	C_s
2008	C	S	W	C	S	C	S	W	C	W	S	C_s	W_s	S
2007	C	S	W	S	C	W	C	S	S	C	W	S	C_s	W_s
2006	C	S	W	C	S	S	W	C	W	S	C	W_s	S	C_s
2005	C	S	W	S	C	C	S	W	C	W	S	C_s	W_s	S
2004	C	S	W	C	S	W	C	S	S	C	W	S	C_s	W_s
2003	C	S	W	S	C	S	W	C	W	S	C	W_s	S	C_s
2002	C	S	W	C	S	C	S	W	C	W	S	C_s	W_s	S

† Continuous: C = continuous corn, S = continuous soybean, W = continuous wheat; CS, corn alternated annually with soybean; CSW, corn followed by soybean followed by wheat; CWS, corn followed by wheat followed by soybean; C_sW_sS, corn followed by wheat followed by soybean rotation system used to mimic a livestock operation in which corn was harvested as silage (C_s), and wheat straw was removed (W_s) where appropriate.

in Table 1. Different corn hybrids were used in 2012 due to seed availability. Fertilizers and pesticides were applied according to University of Wisconsin–Madison best management recommendations (Cullen et al., 2012; Laboski and Peters, 2012). The center two rows of the corn grain and silage plots were harvested with a Kincaid plot combine (Kincaid Equipment Manufacturing, Haven, KS), and the center two rows of the soybean plots and center 1.52 m of the wheat plots were harvested with an Almaco plot combine (Allen Machine Co., Nevada, IA). Grain weights and moisture recorded from each crop were converted to Mg ha^{-1} and adjusted to moisture content of 155 g kg^{-1} (corn) and 130 g kg^{-1} (soybean and wheat). Corn silage weights were adjusted to 650 g kg^{-1} moisture content. Wheat yield in the continuous wheat rotation (WW) was not collected in 2010 and 2011. Yield within this rotation during both years was zero due to poor plant stands and grass weed control issues.

Statistical Analyses

The yield from each plot was used for statistical analysis. Mixed-model analysis of variance was conducted using the PROC GLIMMIX procedure in SAS Version 9.3 (SAS Institute Inc., Cary, NC). Models were constructed and analyzed individually for each crop. Corn was split into corn grain and corn silage. Crop rotation, cultivar rotation, fungicide use, and all two-way and three-way interactions were considered fixed effects. Year was also considered a fixed effect to determine interactions involving year. Replication(year), replication × crop rotation(year), replication × crop rotation × cultivar rotation(year), and the overall error term were considered random effects. Because only one crop rotation utilized corn harvested for silage, the effect of crop rotation could not be examined. When examining corn silage yield, cultivar rotation, fungicide use, and cultivar rotation × fungicide use were considered fixed effects, and replication(year), replication × cultivar rotation(year), and the overall error term were considered random effects. For the wheat in fall 2011, the rotation of the resistant cultivar to the susceptible cultivar within the RRS rotation and the rotation of the susceptible cultivar to the resistant cultivar within the SSR rotation were not made. Therefore, the effect of cultivar rotation for wheat could not be examined. The analysis of the wheat data was conducted in similar fashion to the other crops except the effect of cultivar selection (i.e., RRR vs. SSS) was examined instead of cultivar rotation. In addition, the WW rotation was dropped from the analysis for wheat grain because yield data were not collected for this rotation in two out of three years. For all analyses, fixed effects were tested for significance at $\alpha = 0.10$, and means comparisons were calculated based on Fisher's protected LSD. Degrees of freedom were calculated using the Kenward–Rogers method (Littell et al., 2006).

RESULTS AND DISCUSSION

Environment

Air temperatures in April to June and September were lower in 2011 than in 2010 and 2012 (Table 3). Air temperatures were similar to the 30-yr average for all other months, except for higher temperatures experienced in July 2012. Above-average rainfall occurred in 2010 and was higher than amounts in 2011 and 2012. Rainfall in 2011 was lower than normal in May to August. In 2012, total precipitation was below normal, except in July when all precipitation was received after 15 July. Drought conditions were experienced from June through mid-July in 2012 (U.S. Drought Monitor, 2012).

Table 3. Mean monthly air temperature and total monthly precipitation during the 2010–2012 growing seasons and during the past 30 yr.

Weather variable	2010	2011	2012	30 yr
Air temperature (°C)				
Apr.	9.4	5.0	6.7	7.8
May	13.9	12.2	15.0	13.9
June	18.9	18.3	20.0	19.4
July	21.7	22.8	24.4	21.7
Aug.	21.1	20.0	19.4	20.6
Sept.	14.4	13.9	14.4	16.1
Average	16.6	15.4	16.7	16.6
Precipitation (mm)				
Apr.	94.0	88.9	78.7	88.9
May	106.7	40.6	73.7	94.0
June	193.0	104.1	7.6	116.8
July	236.2	63.5	109.2	104.1
Aug.	119.4	38.1	73.7	96.5
Sept.	114.3	99.1	25.4	91.4
Total	863.6	434.3	368.3	591.7

Corn Grain

Yields were significantly higher in 2010 (15.56 Mg ha^{-1}) than in both 2011 (11.69 Mg ha^{-1}) and 2012 (10.94 Mg ha^{-1}). However, no yield difference was found between 2011 and 2012, even with drought conditions experienced in 2012 (U.S. Drought Monitor, 2012). A significant crop rotation effect was observed, but this effect was influenced by year variability (Table 4). The effect of crop rotation was significant in 2010 and 2012, but no differences in yield were found in 2011. In 2010, grain yield in the corn followed by soybean followed by wheat (CSW) rotation (16.17 Mg ha^{-1}) was 4.6 and 8.3% higher than the corn followed by wheat followed by soybean (CWS) (15.46 Mg ha^{-1}) and continuous corn (CC) (14.93 Mg ha^{-1}) rotations, respectively. No differences in yield were found between the CSW and corn alternated annually with soybean (CS) rotations nor the CS and CWS rotations. In 2012, the CSW rotation (12.54 Mg ha^{-1}) yielded 13.9, 16.4, and 33.0% higher than the CS (11.01 Mg ha^{-1}), CC (10.77 Mg ha^{-1}), and CWS (9.43 Mg ha^{-1}) rotations, respectively. No differences in yield were found between the CS and CC rotations and between the CWS and CC rotations. Across all 3 yr, yield in the CSW rotation was significantly higher than the CC, CS, and CWS rotations (Table 5), with no differences found between the CC, CS, and CWS rotations. The yield difference between the CSW rotation

Table 4. Results from the analysis of variance for fixed main effects and interactions for corn grain, corn silage, soybean, and wheat yield, 2010 to 2012.

Source of variation	Corn Grain	Corn Silage	Soybean	Wheat
Year (Y)	**	***	***	**
Crop rotation (CR)	*	–‡	***	***
Y × CR	†	–	*	***
Cultivar rotation (VR)	*	†	***	***
Y × VR	NS§	NS	***	*
CR × VR	NS	–	NS	*
Y × CR × VR	**	–	**	NS
Fungicide use (FUNG)	NS	NS	†	**
Y × FUNG	NS	NS	NS	***
CR × FUNG	†	–	***	*
Y × CR × FUNG	NS	–	NS	*
VR × FUNG	NS	NS	NS	*
Y × VR × FUNG	NS	NS	NS	NS
CR × VR × FUNG	NS	–	NS	NS
Y × CR × VR × FUNG	NS	–	*	NS

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

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

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

† Significant at the $P = 0.10$ probability level.

‡ Not included in the analysis.

§ NS, no significant differences at $P \leq 0.10$.

Table 5. Crop rotation, cultivar rotation, and fungicide use effect on corn grain, corn silage, soybean, and wheat yield, 2010 to 2012.

Main effect	Corn Grain	Corn Silage	Soybean	Wheat
	Mg ha^{-1}			
Crop rotation (CR)†				
CC	12.60	–‡	–	–
SS	–	–	3.40	–
WW	–	–	–	–
CS	12.60	–	3.93	–
CSW	13.55	–	4.13	5.62
CWS	12.17	–	4.21	4.70
C_sW_sS	–	15.12	4.26	5.26
$LSD_{0.10}$	0.66	–	0.16	0.24
Cultivar rotation (VR)§				
RRR	12.90	14.80	4.14	4.89
SSS	12.56	15.75	3.86	5.50
SSR	12.91	15.82	4.02	–
RRS	12.56	14.79	3.92	–
$LSD_{0.10}$	0.25	0.90	0.09	0.15
Fungicide use (FUNG)				
Untreated	12.80	15.20	3.957	5.09
Treated	12.66	15.38	4.014	5.29
$LSD_{0.10}$	NS¶	NS	0.055	0.12

† CC, continuous corn; SS, continuous soybean; WW, continuous wheat; CS, corn alternated annually with soybean; CSW, corn followed by soybean followed by wheat; CWS, corn followed by wheat followed by soybean; C_sW_sS, corn followed by wheat followed by soybean rotation system used to mimic a livestock operation in which corn was harvested as silage (C_s), and wheat straw was removed (W_s) where appropriate.

‡ Not included in the analysis.

§ Cultivars used were chosen based on their relative resistance (R) or susceptibility (S) to important *Fusarium* pathogens regarding each crop and were arranged in the following rotations: RRR, resistant followed by resistant followed by resistant; SSS, susceptible followed by susceptible followed by susceptible; SSR, susceptible followed by susceptible followed by resistant; RRS, resistant followed by resistant followed by susceptible.

¶ NS, no significant differences at $P \leq 0.10$.

compared to each of the other three rotations ranged from 7.5 to 11.3%. Our data from the combined 3 yr contradicts previous research that showed a 10 to 17% increase in corn yield from annually rotated corn compared to continuous corn (Crookston et al., 1991; Meese et al., 1991; Pedersen and Lauer, 2002, 2003) and also contradicts Lund et al. (1993), who found no corn yield advantage in a CSW rotation compared to CS and CWS rotations. However, our data are consistent with Stanger and Lauer (2008), who observed no difference between CC and CS rotations. Stanger and Lauer (2008), who evaluated corn grain yield response to six crop rotations and four nitrogen rates over 35 yr, suggested external inputs of nitrogen fertilizer negate the true value of crop rotation. We also speculate the more recent corn hybrids used in the current study may be more suitable for a continuous corn rotation compared to the hybrids used by Crookston et al. (1991), Meese et al. (1991), and Pedersen and Lauer (2002, 2003) due to specific transgenic traits (e.g., *Bacillus thuringiensis* traits for corn rootworm [*Diabrotica* spp.] control). Edgerton et al. (2012) reported increased yield and yield stability with corn hybrids containing insect-resistance traits compared to their isogenic, nontraited counterparts, but the authors also caution that insect-resistance traits can have little effect on yield under favorable growing conditions (i.e., yields of nontraited hybrids are high).

For the cultivar rotations, the RRR and SSR rotations yielded significantly higher than the SSS and RRS rotations (Table 5). No difference was found between SSS and RRS rotations. Visible symptoms of ear and stalk rot on corn, primarily caused by *Fusarium verticillioides* and *F. graminearum*, were extremely low each year (data not shown). Other diseases, such as anthracnose stalk rot (*Colletotrichum graminicola*) and common rust (*Puccinia sorghi*), were present each year, but levels were also low (data not shown). The low amount of disease pressure may explain the mixed results for the differences between the cultivar rotations. Furthermore, the use of different corn hybrids in 2012 due to seed availability may have also contributed to these mixed results.

A year × crop rotation × cultivar rotation interaction was observed (Table 6). The crop rotation × cultivar rotation interaction was significant in 2011 and 2012 but not in 2010. Crop rotation primarily affected this interaction. For 2011 and 2012 combined, only two statistical differences were found between cultivar rotations within a crop rotation. In 2011 within the CWS crop rotation, the SSR

Table 6. Year × crop rotation × cultivar rotation effect on corn grain yield, 2010 to 2012.

Main effect	Year × crop rotation†			
	CC	CS	CSW	CWS
Cultivar rotation‡	Mg ha^{-1}			
2010				
RRR	15.48	15.22	16.77	15.62
SSS	14.67	16.23	15.61	15.55
SSR	15.22	15.81	15.99	15.84
RRS	14.35	15.51	16.31	14.82
$LSD_{0.10}$	NS§			
2011				
RRR	12.47	11.04	12.49	10.81
SSS	11.63	11.03	11.77	12.09
SSR	12.19	11.55	11.43	12.18
RRS	12.09	10.80	12.08	11.46
$LSD_{0.10}$	1.31			
2012				
RRR	10.29	11.40	12.84	10.37
SSS	10.99	10.66	12.09	8.45
SSR	10.49	11.26	13.03	9.90
RRS	11.34	10.72	12.21	8.99
$LSD_{0.10}$	1.44			

† CC, continuous corn; CS, corn alternated annually with soybean; CSW, corn followed by soybean followed by wheat; CWS, corn followed by wheat followed by soybean.

‡ Cultivars used were chosen based on their relative resistance (R) or susceptibility (S) to important *Fusarium* pathogens regarding each crop and were arranged in the following rotations: RRR, resistant followed by resistant followed by resistant; SSS, susceptible followed by susceptible followed by susceptible; SSR, susceptible followed by susceptible followed by resistant; RRS, resistant followed by resistant followed by susceptible.

§ NS, no significant differences at $P \leq 0.10$.

cultivar rotation was significantly higher than the RRR cultivar rotation, and in 2012 within the CWS crop rotation, the RRR cultivar rotation was higher than the SSS cultivar rotation. The mixed results for the performance of the cultivar rotations may be due to the low amount of disease observed in 2011 and 2012 coupled with the hybrid change in 2012. Below-average in-season rainfall during 2011 and 2012 likely explains why a low amount of disease pressure was observed.

A crop rotation × fungicide use interaction was also observed (Table 4). Again, crop rotation was the driving factor. Using a fungicide did not significantly increase yield for any of the crop rotations (data not shown). A lack of fungicide response could be due to a combination of the early application timing (V5) in which common foliar diseases do not develop symptoms until later in the growing season and generally low foliar disease pressure observed each year (data not shown). Later fungicide applications (VT to R1) have also demonstrated mixed results for increasing yield and are unlikely to be profitable when foliar disease pressure is low (Paul et al., 2011).

Corn Silage

Average corn silage yield responded similarly to corn grain yield each year. Yield was significantly higher in 2010 (20.04 Mg ha^{-1}) than in 2011 (12.60 Mg ha^{-1}) and 2012 (13.22 Mg ha^{-1}). No difference was found between 2011 and 2012. Cultivar rotation was the only significant effect observed (Table 4). The SSR and SSS cultivar rotations yielded significantly higher than RRR and RRS rotations (Table 5). No difference was observed between the RRR and RRS rotations. Observed disease pressure was similar to that of the corn grain (data not shown). While the cultivar rotation results here are different from those for corn grain, we believe the differences can be attributed to the inherent yield potential differences of the corn hybrids used coupled with the low amount of foliar disease observed.

Soybean

Average soybean yields significantly declined each year from 4.48, 4.18, and 3.29 Mg ha^{-1} in 2010, 2011, and 2012, respectively. Year variability influenced crop rotation (Table 4), but crop rotation still had a significant impact on yield each year. In 2010, no differences were observed between the CWS (4.89 Mg ha^{-1}), corn followed by wheat followed by soybean in which corn was harvested as silage and wheat straw was removed where appropriate (C_sW_sS) (4.75 Mg ha^{-1}), and CSW (4.62 Mg ha^{-1}) rotations, but each crop rotation containing wheat yielded significantly higher than the CS rotation (4.28 Mg ha^{-1}). The CS rotation yielded 10.0% significantly higher than the continuous soybean (SS) rotation. In 2011, the only difference was the SS rotation (3.65 Mg ha^{-1}) yielded lower than all other rotations. For 2012, the C_sW_sS rotation (3.86 Mg ha^{-1}) yielded the highest. No differences were found between the CSW (3.36 Mg ha^{-1}), CWS (3.33 Mg ha^{-1}), and CS (3.28 Mg ha^{-1}) rotations, but each yielded significantly higher than continuous soybean (2.64 Mg ha^{-1}). Across the 3 yr, the crop rotations containing wheat yielded the highest (Table 5). The average of those three rotations combined yielded 6.8% higher than the CS rotation, and the CS rotation yielded 15.8% higher than the SS rotation. The advantage of annually rotated soybean compared to continuous soybean in this study is similar to other reports (Copeland et al., 1993; Crookston et al., 1991; Edwards et al., 1988; Pedersen and Lauer, 2003). However, our results of introducing wheat into the rotation for increasing soybean yield contradict other studies that found no yield advantage for incorporating small grains into CS rotations (Edwards et al., 1988; Peterson and Varvel, 1989). This discrepancy may be due to differences in environment and the small grain used in the rotation. Edwards et al. (1988) used wheat in the rotation, but the study was conducted in northeast Alabama; whereas Peterson and Varvel (1989) performed their study in Nebraska, but used oats (*Avena sativa* L.) instead of wheat in the rotation.

Year variability also influenced cultivar rotation (Table 4). Cultivar rotation was significant in 2011 and 2012 but not in 2010. In 2011, the RRS (4.31 Mg ha^{-1}) and RRR (4.24 Mg ha^{-1}) rotations yielded significantly higher than the SSS (4.13 Mg ha^{-1}) and SSR (4.03 Mg ha^{-1}) rotations, and a significant difference was found between the SSS and SSR rotations. Slightly different results were observed in 2012. The RRR (3.66 Mg ha^{-1}) and SSR (3.54 Mg ha^{-1}) rotations increased soybean yield compared to the SSS (3.08 Mg ha^{-1}) and RRS (2.90 Mg ha^{-1}) rotations, and no difference was found between the SSS and RRS rotations. Across the 3 yr, the RRR rotation significantly yielded 3.0% better than the next highest rotation (SSR), and the SSR rotation yielded 2.4 and 4.1% significantly higher than the RRS and SSS rotations, respectively (Table 5). Sudden death syndrome, caused by *Fusarium virguliforme*, is the major *Fusarium*-related disease on soybean. No SDS symptoms were found during the course of this experiment, and historically, SDS has not been visually confirmed within this rotation study. However, the parallel study examining the influence of these management practices on *Fusarium* spp. populations found *F. virguliforme* was present in 6.2% of plots examined (Marburger et al., 2015). Because *F. virguliforme* was present but SDS symptoms were not observed, this may only partially explain why the RRR rotation yielded the highest. Symptoms of other common soybean diseases found in Wisconsin, such as white mold (*Sclerotinia sclerotiorum*), brown stem rot (*Phialophora gregata*), and *Phytophthora* root and stem rot (*Phytophthora sojae*), were not visible or were at extremely low levels each year (data not shown). Symptoms of *Septoria* brown spot (*Septoria glycines*) were visible each year, but the severity of the disease was not at levels which warranted additional control. Because of the low amount of disease pressure observed overall and because no SDS symptoms were visible, we believe the cultivar rotation results observed were most likely due to the inherent yield potential of the cultivar and less likely due to the ability of the RRR rotation to reduce the amount of disease symptoms expressed as would be expected.

A year × crop rotation × cultivar rotation interaction was also found (Table 7). Crop rotation × cultivar rotation was significant in 2011 and 2012 but not in 2010. Again, crop rotation appeared to be the main driver, but the RRR rotation was consistently part of the statistically highest yields for each crop rotation within 2011 and 2012.

Fungicide seed treatment use increased yield by 1.4% on average (Table 5). Other reports have shown an increase in yield from fungicide seed treatment use, but the positive response in yield is often year and location dependent (Bradley, 2008; Dorrance et al., 2009; Esker and Conley, 2012; Gaspar et al., 2014). A crop rotation × fungicide use interaction was observed. However, use of a fungicide seed treatment only significantly increased yield in the C_sW_sS rotation.

Table 7. Year × crop rotation × cultivar rotation effect on soybean grain yield, 2010 to 2012.

	Year × crop rotation†				
Main effect	SS	CS	CSW	CWS	C_sW_sS
Cultivar rotation‡			Mg ha^{-1}		
2010					
RRR	3.93	4.42	4.42	5.00	4.81
SSS	3.79	4.18	4.57	4.88	4.48
SSR	3.92	4.30	4.82	4.77	4.60
RRS	3.92	4.22	4.66	4.91	5.11
$LSD_{0.10}$			NS§		
2011					
RRR	3.79	4.10	4.35	4.62	4.35
SSS	3.70	4.32	4.30	4.19	4.12
SSR	3.39	4.01	4.34	4.41	3.98
RRS	3.73	4.49	4.60	4.44	4.27
$LSD_{0.10}$			0.30		
2012					
RRR	2.95	3.62	3.94	3.45	4.33
SSS	2.47	2.90	2.85	3.56	3.61
SSR	2.93	3.57	3.42	3.47	4.32
RRS	2.22	3.05	3.25	2.82	3.18
$LSD_{0.10}$			0.45		

† SS, continuous soybean; CS, corn alternated annually with soybean; CSW, corn followed by soybean followed by wheat; CWS, corn followed by wheat followed by soybean; C_sW_sS, corn followed by wheat followed by soybean rotation system used to mimic a livestock operation in which corn was harvested as silage (C_s), and wheat straw was removed (W_s) where appropriate.

‡ Cultivars used were chosen based on their relative resistance (R) or susceptibility (S) to important *Fusarium* pathogens regarding each crop and were arranged in the following rotations: RRR, resistant followed by resistant followed by resistant; SSS, susceptible followed by susceptible followed by susceptible; SSR, susceptible followed by susceptible followed by resistant; RRS, resistant followed by resistant followed by susceptible.

§ NS, no significant differences at $P \leq 0.10$.

There was evidence of a year × crop rotation × cultivar rotation × fungicide use interaction; however, there was no discernable biological importance noted from this interaction.

Wheat

The effect of crop rotation, cultivar selection, and fungicide use varied with year (Table 4). Average wheat yields significantly increased each year from 4.67, 5.14, and 5.76 Mg ha^{-1} in 2010, 2011, and 2012, respectively. Crop rotation was significant in 2011 and 2012 but not in 2010. In 2011, the CSW rotation (6.03 Mg ha^{-1}) yielded 11.5% higher than the C_sW_sS rotation (5.41 Mg ha^{-1}), and the C_sW_sS rotation yielded 36.6% higher than the CWS rotation (3.96 Mg ha^{-1}). In 2012, the CSW rotation (6.34 Mg ha^{-1}) yielded 15.6 and 15.9% better than the CWS (5.48 Mg ha^{-1}) and C_sW_sS (5.47 Mg ha^{-1}) rotations, respectively. No difference was found between the CWS and C_sW_sS rotations. Across all 3 yr, the CSW rotation yielded 6.8 and 19.6% better than the C_sW_sS and CWS rotations, respectively, and the C_sW_sS rotation yielded 12.0% better than the CWS rotation (Table 5). This data is similar to

Dill-Macky and Jones (2000), who found wheat yields were better following soybean compared to following corn. *Fusarium* head blight, caused by *Fusarium graminearum*, is the major *Fusarium*-related disease on wheat. Because *F. graminearum* can survive on aboveground residues (Cotten and Munkvold, 1998), decreased inoculum of *F. graminearum* from wheat following soybean in the CSW rotation and through the removal of corn and wheat residues in the C_sW_sS rotation may explain the observed yield differences. However, Marburger et al. (2015) reported no differences in FHB incidence and severity between the CSW, CWS, and C_sW_sS rotations each year. That study also showed presence of *F. graminearum* in the soil was similar among the three rotations. *Fusarium graminearum* has been shown to cause seedling disease on soybean (Broders et al., 2007; Pioli et al., 2004); therefore, because *F. graminearum* can survive and reproduce on soybean, this may clarify why Marburger et al. (2015) found no differences in FHB incidence and severity and *F. graminearum* presence in the soil.

A year × cultivar selection interaction was observed (Table 4). However, in each year the susceptible cultivar yielded significantly higher than the resistant cultivar, even with FHB observed each year (Marburger et al., 2015). Across the 3 yr, the susceptible cultivar yielded 12.4% better on average than the resistant cultivar (Table 5). A crop rotation × cultivar selection interaction was also observed. For each crop rotation, the susceptible cultivar yielded significantly higher than the resistant cultivar. Although FHB was observed each year, these results suggested this particular FHB-susceptible cultivar had a higher yield potential than the resistant cultivar. Similar results between these two cultivars were observed in the 2010 and 2011 Wisconsin winter wheat cultivar trials (Conley et al., 2010b, 2011). While the focus of this study was choosing cultivars with relative resistance and susceptibility to *Fusarium*-causing diseases, these results stress the importance for growers to begin with selecting the highest potential yielding cultivars in addition to choosing resistance packages for yield-limiting diseases in their fields for maximizing yield.

Fungicide use for control of FHB increased yield 3.9% on average (Table 5). Other reports have found similar results (Cromey et al., 2001; Jones, 2000). However, this effect was not consistent each year. Fungicide use increased yield in 2010 and 2012, but there was no benefit in terms of yield from using a fungicide in 2011 despite observing the highest incidence and severity of FHB (Marburger et al., 2015). *Fusarium* head blight levels in 2010 were only slightly less than levels observed in 2011, however, and extremely low levels of FHB were observed in 2012 due to hot and dry conditions. Symptoms of other common wheat diseases found in Wisconsin, including powdery mildew (*Blumeria graminis* f. sp. *tritici*) and leaf rust (*Puccinia triticina*), were present in 2010 and 2011 (data not shown), but the amount of disease present did not warrant additional control to minimize any potential confounding effects. Extremely low levels of non–*Fusarium*-related diseases were observed in 2012, again due to hot and dry conditions.

A year × crop rotation × fungicide use interaction was observed, but it was only significant in 2011. In 2011, fungicide use did not increase yield in the CWS and C_sW_sS rotations, and decreased yield was observed in the CSW rotation (6.44 to 5.63 Mg ha^{-1}). Across all 3 yr, using a fungicide significantly increased yield in the CWS (4.49 to 4.90 Mg ha^{-1}) and C_sW_sS rotations (5.12 to 5.40 Mg ha^{-1}) but not in the CSW rotation. However, the CSW treated (5.57 Mg ha^{-1}) and untreated (5.66 Mg ha^{-1}) yield was still statistically higher than all other combinations of crop rotation and fungicide use besides the treated C_sW_sS rotation (5.40 Mg ha^{-1}). Because wheat followed corn in the C_sW_sS and CWS rotations, this may have led to a buildup of *F. graminearum* inoculum, which could explain the positive yield response to fungicide use for these two rotations across all 3 yr, but, again, no difference in FHB incidence and severity was found between the CSW, C_sW_sS, and CWS rotations each year during the duration of this study (Marburger et al., 2015).

A cultivar selection × fungicide use interaction was also observed (Table 4). Fungicide use increased yield in the susceptible cultivar 7.2% (5.31 to 5.69 Mg ha^{-1}) but did not significantly increase yield for the resistant cultivar. Nonetheless, the susceptible cultivar treated and untreated yielded significantly higher than the resistant cultivar treated (4.89 Mg ha^{-1}) and untreated (4.88 Mg ha^{-1}). Studies have shown incorporating a resistant cultivar with an appropriately timed fungicide application can result in the greatest reduction of FHB incidence and severity, but results can vary (Willyerd et al., 2010, 2012). Marburger et al. (2015) found no evidence of a cultivar selection × fungicide use interaction for control of FHB during the course of the current study, except for FHB percent incidence in 2010. The results from this study suggest choosing a cultivar with high yield potential, and if that cultivar is susceptible to FHB, then fungicide use can increase yield.

CONCLUSIONS

This study aimed at identifying interactions among crop rotation, cultivar rotation, and fungicide use to increase corn, soybean, and wheat yields, with emphasis of these management practices aimed at controlling diseases caused by *Fusarium* spp. For corn grain, significant interactions were primarily driven by crop rotation, with highest corn yields across all 3 yr observed in the CSW rotation (13.55 Mg ha^{-1}). Corn silage yield was influenced by cultivar rotation, with highest yields displayed by the SSS and SSR rotations. Soybean yields were influenced by interactions involving crop rotation and cultivar rotation. Highest soybean yields were found for crop rotations containing wheat and ranged from 5.1 to 8.4% higher than the CS rotation. The RRR cultivar rotation (4.14 Mg ha^{-1}) yielded 3.0% better than the next highest rotation (SSR). For wheat, crop rotation, cultivar selection, and fungicide use were all key drivers. Highest wheat yields on average were observed in the CSW rotation (5.62 Mg ha^{-1}). The FHB-susceptible cultivar (5.50 Mg ha^{-1}) yielded significantly higher compared to the resistant cultivar (4.89 Mg ha^{-1}), and fungicide use increased yield in the susceptible cultivar 7.2% (5.31 to 5.69 Mg ha^{-1}) but not for the resistant cultivar. Although significant interactions identified between these management strategies were not consistent for all three crops, our results show the CSW crop rotation was one of the most important management strategies for maximizing corn, soybean, and wheat yields. Furthermore, our results suggest using a cultivar with high yield potential, regardless of its relative resistance or susceptibility to important *Fusarium* pathogens, versus consistently using a resistant cultivar or rotations between resistant and susceptible cultivars. While response to fungicide use was not consistent for all three crops, integrated pest management principles, such as scouting and treatment at threshold, should continue to be utilized to warrant a foliar fungicide application. In conclusion, for managing *Fusarium*-related diseases, our results recommend growers should begin by combining a high-yield-potential cultivar, regardless of its susceptibility or resistance to *Fusarium* pathogens, in a CSW crop rotation to maximize yield potential. Although growers strive to maximize yield, maximizing profit is often their end goal. An economic analysis was not performed on these data, but an economic analysis would be the next step to help provide growers with better disease management recommendations.

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