Wheat Grain and Straw Yield, Grain Quality, and Disease Benefits Associated with Increased Management Intensity

Authors: Mitchell G. Roth, Spyridon Mourtzinis, John M. Gaska, Brian Mueller, Adam Roth, Damon L. Smith, and Shawn P. Conley

A FEW KERNELS

▶ Integrating applications of growth regulators, micronutrients, fungicides, an increased seeding rate, and higher N rates led to increased wheat grain yield, grain test weight, and straw yield across winter wheat varieties in Wisconsin.

▶ One or two fungicide applications successfully reduced the incidence and severity of Fusarium head blight (FHB) and DON levels in grain. Two fungicide applications were required to successfully reduce the incidence and severity of stripe rust during the years of this study.

▶ While the intensified management practices require additional expenditures, the yield benefits make them profitable. Compared to the current management level, the mid-level management technique resulted in an additional $124 per acre, and the high-level management plan resulted in an additional $98 per acre.

INTRODUCTION

Winter wheat is a very important crop in the U.S. where an average of 53 million acres have been planted since 2000 (McMullen et al., 2012; USDA NASS, 2020). During the Green Revolution from the 1960's through 1980's, many advances in wheat genetics and new varieties led to significant advances in wheat production (Bell et al., 1995; Brancourt-Hulmel et al., 2003), Since then, yield gains have plateaued in many wheat-producing regions, including in the U.S. (Lollato et al. 2019).

Germplasm selection, management intensity, and inputs are important considerations for farmers. A Swiss study examining 20 years of winter wheat data shows that genetics explains more variation under a high-input management approach than a low-input or organic approach (Herrera et al. 2020), suggesting that high-input management can optimize yields across varieties and enhance knowledge about variety yield potential. Soft red winter wheat has higher yield potential than hard red winter wheat (Lollato et al. 2020), and soft red varieties are commonly grown in Wisconsin. Many different management tactics have been studied for their effects on wheat grain yield, including applications of N and P fertilizers, seeding rates, plant growth regulators, micronutrient applications, and a combination of approaches. Recent studies examining integrated approaches of multiple management practices indicate that intensified management boosts grain yields in Kansas (Jaenisch et al., 2019; de Oliveira Silva et al., 2020), but not in Michigan (Quinn & Steinke, 2019).Therefore, additional inputs may be worthwhile if they lead to higher yields. However, additional inputs require additional expenditures, and the economic value of wheat grain has decreased in recent years. Therefore, farmers that continue to grow winter wheat have a desire to mitigate yield losses and boost yields through a wide range of management tactics, if they are economical.

Wheat is also susceptible to many economically important diseases, like Fusarium head blight (FHB) and stripe rust. Wheat affected by FHB can have reduced grain yield and kernel test weights, causing an average economic loss of over $250 million USD per year from 1993-2001 (Nganje et al., 2004; Salgado et al., 2015). FHB infected grain commonly contains a mycotoxin called deoxynivalenol (DON) that is very stable through grain processing and is toxic to humans and animals (Pestka 2007; Nishio et al., 2010). Globally, stripe rust causes yield losses worth an estimated $979 million USD each year (Beddow et al., 2015). A severe stripe rust outbreak occurred in northern states, including Wisconsin, in 2016 (Mueller et al., 2020). Farmers can protect wheat yields from FHB and stripe rust through various management techniques. Fungicide applications are the primary method of control for these foliar wheat diseases in the U.S. (Chen, 2014; Chen & Kang, 2017), but genetic resistance for stripe rust (Schwessinger, 2017; Mueller et al., 2020) and FHB (da Silva et al., 2019) have also been identified and bred into wheat varieties.

From 2000 to 2020, total area planted in wheat in the U.S. has decreased significantly, while total grain production has remained relatively stable (Figure 1). Intensifying management of wheat, including disease management, proper weed control, and adequate nutrient supply, may help explain how wheat production has been maintained despite a significant decrease in wheat area planted in the U.S. In this study, we sought to determine if higher management intensity indeed led to higher yields, better grain quality, and reduced disease in Wisconsin. In addition, we examined the economic costs and returns on investments for the intensified management strategies in wheat production to determine their profitability for Wisconsin wheat farmers.

Figure 1. Total area of U.S. wheat production (left y-axis) and total grain production (right y-axis) since 2000. Total area planted each year and quadratic line of best fit (r2 = 0.82, P < 0.001) are represented by black circles and a solid black line, respectively. Total wheat production each year and linear line of best fit (P = 0.679) are represented by grey triangles and a grey dashed line, respectively. Grey shading surrounding the quadratic line of best fit for area planted represents 95% confidence interval.
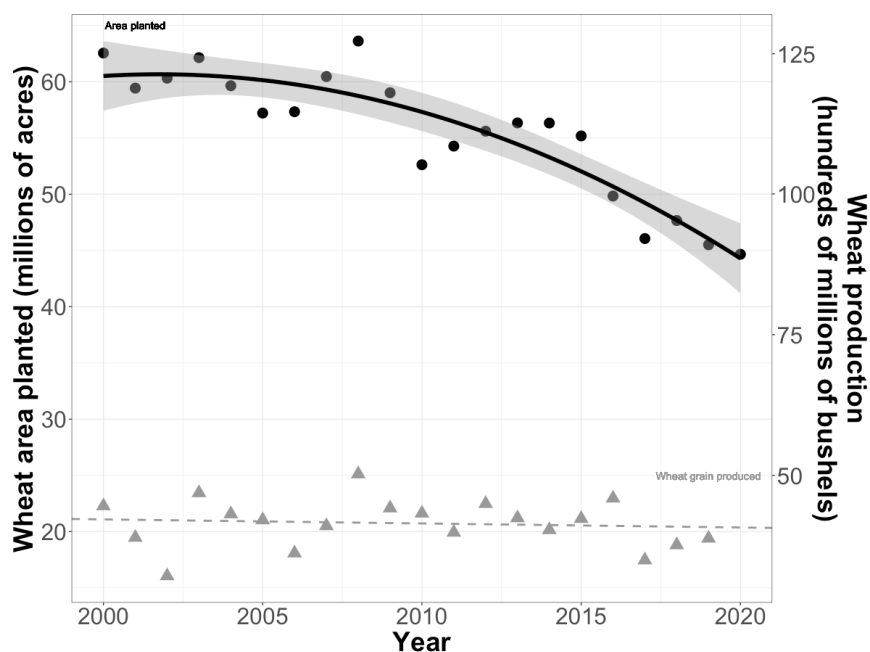
MATERIALS AND METHODS

Experimental Design

All field trials were conducted at the Arlington Agricultural Research Station in Arlington, WI during 2016-2019. All plots measured 7.5 ft by 25 ft, with wheat planted into existing soybean residue at 1 inch depth, 7.5-inch row spacing, and a total of 9 rows. Winter wheat was sown between Sept. 23 and Oct 4 in all years. The center 7 rows of each wheat plot were harvested for grain yield measurements. Straw yield was measured in 2018 and 2019 on a management-wide basis instead of plot-wise. After grain harvest, the straw from each main block of management practice was chopped into a wagon and weighed. A sub-sample of straw from each block was used for a moisture measurement, determined by weighing before and after drying. In all years, a randomized complete block split plot design was used with four replicates and wheat varieties randomized within each block of management intensity. A total of 20 varieties were examined, with at least 14 wheat varieties examined each year. To view

the detailed performance of individual varieties, please see the Wisconsin Winter Wheat Performance Trials Data.

Wheat management practices included combinations of differences in seeding rates, nitrogen applications, growth regulators, micronutrient applications, and fungicide applications. Different combinations of these management practices were compiled into three intensity categories; "current", "mid-level", or "high-level". The current management approach uses approaches commonly used by wheat farmers in Wisconsin (Laboski & Peters, 2012). The mid- and high-level management practices include additional applications considered to benefit wheat health and protect yields, including the application of fungicides, growth regulators, and micronutrients. All management approaches used Huskie herbicide (Bayer, St. Louis, MO, USA). All growth regulator applications used Palisade (Syngenta, Greensboro, NC, USA). Micronutrient applications used TakeOff Phite MZ (Verdesian Life Sciences, Cary, NC, USA), EB Mix (West Central, Inc, Willmar, MN), and Brandt Smart Quatro Plus (Brandt Inc., Springfield, IL, USA). Fungicide applications used Priaxor (BASF, Ludwigshafen, Germany), Trivapro (Syngenta), Prosaro (Bayer), and/or Miravis Ace (Syngenta). Specific differences in management strategies across years are listed in Table 1.

Table 1. Management practices and application rates across management intensities.

Management intensity	Year	Current	Mid-level	High-level
Base herbicide (Huskie, fl oz / acre)	2016	11	11	11
	2017	15	15	15
	2018	15	15	15
	2019	15	15	15
Seeding rate (million seeds / acre)	All years	1.5	1.75	2.0
Nitrogen rate (lbs N / acre)[a]	2016	55	55 + 17 split	55 + 17 split
	2017	55	55 + 30 split	55 + 30 split
	2018	55	55 + 30 split	110 + 30 split
	2019	55	55 + 30 split	110 + 30 split
Growth Regulator[b] (Palisade, fl oz / acre)	All years	N/A	N/A	12
Micronutrients application 1[c,d] (fl oz / acre)	All years	N/A	N/A	96
Fungicide application 1[c,e] (fl oz / acre)	2016	N/A	N/A	8
	2017			13.7
	2018			13.7
	2019			13.7
Micronutrients application 2[f] (TakeOff Phite MZ, fl oz / acre)	All years	N/A	N/A	32
Fungicide application 2[f,g] (fl oz / acre)	2016	N/A	6.5	6.5
	2017		13.7	13.7
	2018		13.7	13.7
	2019		13.7	13.7

[a] Two applications of Nitrogen were used in all instances where "split" is listed. [b] Applied at wheat growth stage Feekes 6 (Large, 1954). [c] Applied at wheat growth stage Feekes 9 (Large, 1954). [d] In 2016, 2017, and 2018, a tank mix of TakeOff Phite MZ and EB mix was applied at 32 fl oz / acre for TakeOff Phite MZ and 64 fl oz / acre for EB mix. In 2019, a tank mix of Brandt Smart Quatro Plus and EB mix was applied at 32 fl oz / acre for Brandt Smart Quatro Plus and 64 fl oz / acre for EB mix. [e] In 2016, Priaxor was used. In 2017-2019, Trivapro was used. [f] Applied at wheat growth stage Feekes 10.5.1 (Large, 1954). [g] In 2016, Prosaro was applied. In 2017-2019, Miravis Ace was applied.

Disease ratings

In 2016, a severe stripe rust outbreak occurred in Wisconsin and other northern states which was unexpected and is unusual for this disease (Mueller et al., 2020). Consequently, stripe rust intensity was monitored in 2017 by rating disease incidence (percentage of plants with stripe rust) and disease severity (percent of flag leaf covered with lesions). Stripe rust was also monitored in 2018 and 2019, but was not detected. FHB intensity was determined by rating disease incidence (percentage of plants with FHB) and disease severity (percentage of head with symptoms). FHB was not observed in 2016. In 2018 and 2019, a subsample of grain was sent to the University of Minnesota for DON quantification in parts per million (ppm).

Economic evaluation of costs and returns

Average yields were determined for each management intensity level and multiplied by $5 per bushel, the average wheat grain price received since 2000. Costs of herbicide, nitrogen, micronutrients, and fungicides were estimated based on costs of locally available commercial formulations. Cost of seed was determined using an estimated $37 per bushel for certified seed and assuming a bushel of wheat weighs 60 lb. Variable cost of field applications including fuel, oil, and repair costs were estimated according to recent estimates of machinery costs in Iowa (Plastina, 2020). Costs associated with equipment depreciation, interest, insurance, and housing was not estimated or used in these calculations, so additional costs may exist. Deductions in wheat price received due to test weight and DON concentrations were calculated based off of the 2018 Wheat Discount and Storage Schedule of the Landmark Services Cooperative. Briefly, test weights $\geq$ 58 lb per bushel received no deduction, test weights < 58 but $\geq$ 56 lb per bushel received an 8¢ deduction, test weights < 56 but $\geq$ 52 lb per bushel received a 10¢ deduction, and test weights < 52 lb per bushel received a 12¢ deduction. Samples with DON concentrations < 2.1 ppm DON received no deduction, $\geq$ 2.1 but < 3 ppm DON received a 20¢ deduction, $\geq$ 3.1 but < 4 ppm DON received a 30¢ deduction, and > 4 ppm DON were rejected. The frequency of test weight and DON deductions within each management intensity was determined, and this percentage was used in determining the probability of deductions in overall profits per management category.

RESULTS AND DISCUSSION

Increasing management intensity increases wheat grain yield, grain test weight, and straw yield

Management intensity and wheat variety both influenced wheat yield, as did their interaction (P < 0.001). All varieties except SY 547 had a significant increase in grain yield associated with increasing management in at least one year, and increased management intensity significantly increased wheat yields in 46 of the 56 variety x year combinations (Table 2). While yields were significantly higher overall in 2016 than any other year, increasing management intensity was associated with a significant increase in yield across years as well (Figure 2). In addition, straw yield from mid-level and high-level averaged 1.42 US tons / acre, both greater than the current treatment which averaged 0.94 US tons / acre (P < 0.001).

Test weight is an important parameter associated with wheat quality, and farmers can receive price penalties for poor test weight values. Test weight does not consistently correlate with yield (Kelly et al., 1995), so increased yields alone may not lead to higher profit for wheat farmers if test weights are poor. Management intensity and wheat variety influenced wheat test weight, as did their interaction (P < 0.01). Within 17 of the 20 varieties examined, increasing management intensity significantly increased kernel test weight (Table 3). These trends were observed consistently across years as well (Figure 2).

Many years of fertilizing field crops with macronutrients (nitrogen, phosphorus, potassium) can lead to increased yields, but can also lead to soil depleted of micronutrients (iron, zinc, manganese, sufur, boron) (Cakmak, 2009; Dimkpa & Bindraban, 2016). Adding micronutrient applications to wheat can increase yields and enhance zinc

Figure 2. Wheat yield and test weight in response to management intensity, by year. Bars represent treatment means, dots represent individual data points comprising the calculated mean. Dashed horizontal line represents 60 lb per bushel, the threshold at which quality is acceptable and is not subjected to price deductions. ns = P > 0.05, * = P < 0.05, ** = P < 0.01, *** = P < 0.001.
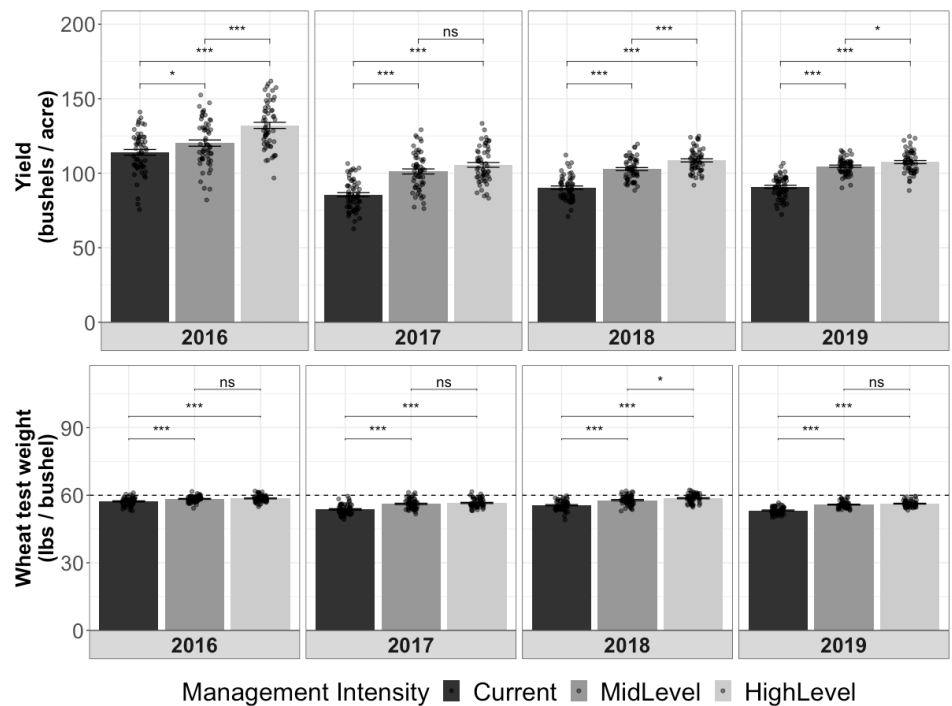

Table 2. Wheat grain yield (bushels per acre) within variety across management intensity. Yields followed by the same letter are not significantly different within variety within year at α=0.05.

Variety	2016 Current	2016 Mid-level	2016 High-level	2017 Current	2017 Mid-level	2017 High-level	2018 Current	2018 Mid-level	2018 High-level	2019 Current	2019 Mid-level	2019 High-level	AVERAGE*
PR25R40	135.8 a	141.4 a	148.6 a	95.3 b	125.4 a	124.3 a	NA	NA	NA	95.3 b	110.8 a	115.3 a	121.3 A
735	123.6 c	137.9 b	154.5 a	86.2 b	103.2 ab	115.6 a	101.0 b	113.0 ab	119.7 b	99.5 a	107.6 a	106.7 a	114.0 AB
Pro 410	126.3 b	136.5 ab	149.4 a	95.7 a	106.7 a	113.4 a	90.8 b	100.9 ab	110.9 a	85.9 b	102.7 a	104.7 a	110.3 ABC
SY 547	129.0 a	129.2 a	138.0 a	90.5 a	105.2 a	104.5 a	97.6 a	104.2 a	106.6 a	90.5 a	106.5 a	106.4 a	109.0 BCD
776	110.4 c	124.8 b	144.0 a	80.9 b	101.3 a	109.7 a	92.3 b	101.1 b	113.7 a	94.3 b	102.8 b	114.9 a	107.5 BCD
KF 15639	NA	NA	NA	NA	NA	NA	NA	NA	NA	99.4 b	109.3 a	112.1 a	106.9 ABCDE
Red Devil	120.0 b	132.6 ab	142.5 a	84.4 b	105.3 a	99.8 a	83.9 b	102.7 a	108.0 a	87.4 b	101.8 a	103.6 a	106.0 BCDE
Pro 260	120.0 b	125.6 b	136.3 a	83.3 b	99.4 ab	106.3 a	86.6 b	101.3 a	105.0 a	88.6 b	104.5 a	106.3 a	105.3 BCDE
Whale	NA	NA	NA	NA	NA	NA	98.4 b	111.8 a	111.4 a	89.1 b	106.3 a	111.1 a	104.7 BCDE
Pro 320A	113.0 a	114.3 a	116.3 a	93.9 a	104.4 a	108.5 a	85.1 b	96.8 ab	101.8 a	NA	NA	NA	103.8 BCDE
FS624	NA	NA	NA	NA	NA	NA	92.4 b	106.1 ab	117.4 a	86.6 b	106.6 a	113.5 a	103.8 BCDE
Kaskaskia	102.8 b	109.8 b	120.9 a	85.3 b	99.3 ab	103.1 a	NA	NA	NA	NA	NA	NA	103.5 BCDE
Pro 380	119.8 b	114.5 ab	124.3 a	90.9 ab	105.3 a	89.2 b	88.3 b	98.6 ab	100.7 a	NA	NA	NA	103.5 BCDE
Pro 240	107.4 b	112.1 b	123.2 a	77.6 b	96.8 a	97.1 a	NA	NA	NA	NA	NA	NA	102.4 BCDE
Harpoon	NA	NA	NA	NA	NA	NA	90.8 b	98.6 ab	104.4 a	94.7 a	101.7 a	104.7 a	99.2 CDE
SRW9606	NA	NA	NA	NA	NA	NA	87.3 b	99.3 a	108.0 a	89.2 b	101.5 ab	107.9 a	98.9 CDE
KF 15241	103.1 b	108.7 ab	122.1 a	79.0 b	90.1 ab	102.9 a	87.3 c	96.6 b	103.4 a	93.2 a	99.1 a	96.6 a	98.5 DE
Sunburst	NA	NA	NA	NA	NA	NA	82.6 b	107.9 a	109.3 a	78.5 b	104.9 a	100.3 a	97.2 CDE
Pro 420	102.4 b	106.5 b	119.8 a	71.4 b	80.4 b	101.1 a	NA	NA	NA	NA	NA	NA	97.0 CDE
Pro 200	82.4 b	88.8 b	109.2 a	83.4 a	93.5 a	102.5 a	NA	NA	NA	NA	NA	NA	93.3 E
AVERAGE†	114.0 c	120.2 b	132.1 a	85.6 b	101.2 a	105.6 a	90.3 c	102.8 b	108.6 a	90.9 c	104.7 b	107.4 a	

* Variety average across all years. Letters in this column denote Tukey HSD groups of significant differences (α = 0.05) in average yield due to variety. † Average yields across all varieties. Letters in this row denote significant differences (α = 0.05) in yield due to management intensity across all yields.

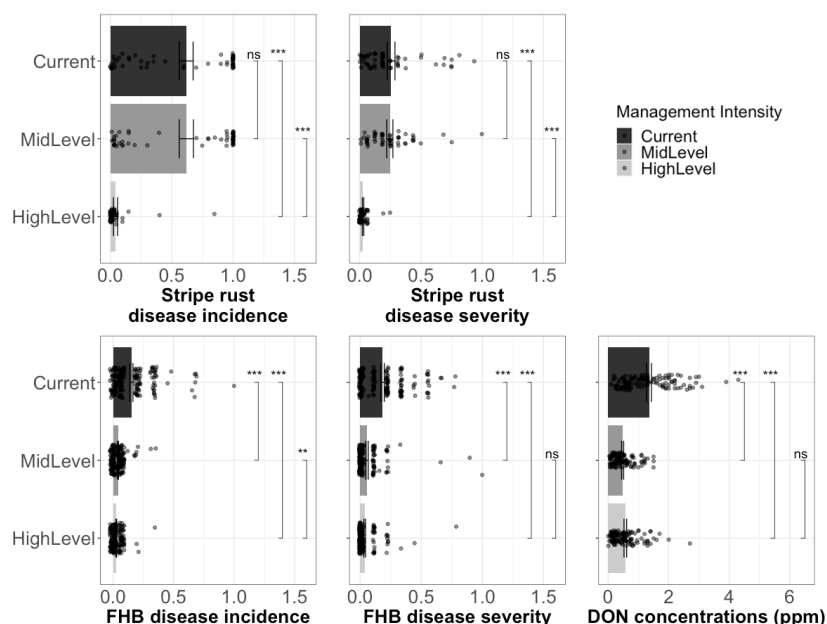content in the grain (Wang et al., 2015; Rietra et al., 2017). The high-level management intensity in this study was the only one containing micronutrient applications, which had the highest yields and test weights compared to other management intensity levels (Table 2, Table 3). Whether the grain harvested from the high-level plots also contained higher levels of zinc or other micronutrients was not investigated in this study.

Increasing management intensity reduces disease

Stripe rust was only detected in 2017. Management intensity and wheat variety both had a significant main effect on stripe rust disease incidence and severity, as did their interaction (P < 0.001). Within 11 of the 14 varieties, the high-level management intensity reduced stripe rust incidence and severity compared to the current management strategy (P < 0.05), indicating that high-level management reduced stripe rust compared to both current and mid-level management intensities (Figure 3).

Figure 3. Stripe rust disease incidence and severity (2017), Fusarium head blight (FHB) disease severity and incidence (2017-2019), and deoxynivalenol (DON) concentrations (2018-2019) in response to management intensity. Bars represent treatment means, dots represent individual data points comprising the calculated mean.
ppm = parts per million, or mg per k
ns = not significant
P > 0.05
*** = P < 0.001

FHB was not detected in 2016. In 2017 to 2019, management intensity and wheat variety both influenced FHB (P < 0.05), as did their interaction (P < 0.001). Management intensity did have an effect on DON concentrations, where mid-level and high-level significantly reduced DON accumulation relative to current management intensity (P < 0.001, Figure 3). The reductions in DON, together with increased overall test weights, reduced the likelihood of grain price deductions (Table 4).

Current stripe rust management recommendations include cultural practices such as the removal of alternate hosts, sowing genetically resistant varieties, and fungicide use (Figueroa et al., 2018; Mueller et al. 2020). The airborne nature of rust spores make them particularly capable of long-distance dispersal, providing ample exposure to susceptible wheat varieties. An estimated 88% of all wheat planted globally is susceptible to stripe rust (Beddow et al., 2015). Thus, fungicide use is the most popular method of stripe rust control in wheat, and multiple chemistries are effective (Oliver, 2014). Current FHB management recommendations are largely centered on fungicide applications, though appropriate timing and chemistry are key to successful management with fungicides (Paul et al., 2008; Pirgozliev et al., 2008). Genetic resistance to FHB is desired, but current progress is slow due to the complex genetic nature of resistance to FHB (Gilbert & Haber, 2013). Crop rotation with non-hosts and deep tillage can also be effective (Figueroa et al., 2018). The results in this study affirm that fungicide use can reduce both stripe rust and FHB incidence and severity (Figure 3), though multiple applications or appropriate timing of a single application may be necessary for appropriate control, particularly for stripe rust (Chen & Kang, 2017; Mueller et al. 2020).

Table 3. Wheat test weight (lbs per bushel) within variety across management intensity. Test weights followed by the same letter are not significantly different within variety within year, at α=0.05.

Variety	2016 Current	2016 Mid-level	2016 High-level	2017 Current	2017 Mid-level	2017 High-level	2018 Current	2018 Mid-level	2018 High-level	2019 Current	2019 Mid-level	2019 High-level	AVERAGE*
Pro 380	60.2 a	60.8 a	61.3 a	57.0 a	59.2 a	57.7 a	58.1 a	59.4 a	59.1 a	NA	NA	NA	59.2 A
Sunburst	NA	NA	NA	NA	NA	NA	56.7 b	61.4 a	61.0 a	54.9 b	58.1 a	58.2 a	58.4 AB
Kaskaskia	58.8 b	59.2 ab	60.6 a	55.3 a	57.6 a	56.8 a	NA	NA	NA	NA	NA	NA	58.0 ABC
KF 15639	NA	NA	NA	NA	NA	NA	NA	NA	NA	55.7 b	58.9 a	58.9 a	57.8 ABCD
Red Devil	57.1 a	588 a	59.0 a	54.7 a	56.4 a	57.0 a	57.1 b	60.4 a	60.2 a	54.4 b	56.7 a	55.9 ab	57.3 BC
Pro 200	55.6 b	59.2 a	58.3 ab	55.7 a	56.2 a	57.6 a	NA	NA	NA	NA	NA	NA	57.1 ABCDE
SY 547	57.8 a	58.2 a	58.2 a	54.3 a	57.3 a	55.6 a	57.0 a	57.6 a	59.2 a	54.2 b	56.3 a	57.0 a	56.9 BCD
KF 15241	57.1 a	58.2 a	58.7 a	53.6 a	56.0 a	57.9 a	55.9 b	58.1 a	59.4 a	55.0 b	56.3 a	56.5 a	56.9 BCD
Pro 410	57.6 b	59.2 a	59.0 b	53.6 b	57.1 a	59.2 a	55.7 b	57.1 b	58.7 a	51.5 b	55.2 a	55.1 a	56.6 BCDE
FS624	NA	NA	NA	NA	NA	NA	55.8 b	59.3 ab	60.2 a	52.5 b	55.3 a	56.4 a	56.6 BCDEF
Pro 420	58.2 a	59.0 a	59.4 a	53.7 a	53.5 a	55.2 a	NA	NA	NA	NA	NA	NA	56.5 BCDEF
PR25R40	58.4 a	58.9 a	58.9 a	52.0 b	56.0 a	55.9 a	NA	NA	NA	53.2 b	55.8 a	56.5 a	56.2 CDEF
Pro 240	56.2 a	57.4 a	57.5 a	52.1 b	57.3 a	56.3 a	NA	NA	NA	NA	NA	NA	56.1 BCDEF
Pro 320A	56.1 a	55.9 a	56.7 a	55.1 a	55.0 a	55.6 a	55.9 a	56.6 a	57.6 a	NA	NA	NA	56.0 CDEF
Whale	NA	NA	NA	NA	NA	NA	55.2 b	58.8 a	58.3 a	52.6 b	55.5 a	55.5 a	56.0 CDEF
735	56.8 a	57.5 a	57.7 a	50.6 b	55.2 a	56.1 a	55.1 b	57.5 a	59.1 a	52.5 b	54.5 a	55.2 a	55.6 DEF
776	54.5 b	57.2 a	57.5 a	52.5 b	53.4 ab	56.4 a	55.6 b	57.1 ab	59.5 a	52.3 b	54.6 a	55.6 a	55.6 DEF
Pro 260	57.5 a	58.0 a	57.2 a	52.1 b	55.7 a	54.7 ab	53.0 a	55.8 a	55.7 a	52.7 b	54.8 a	55.1 a	55.2 EF
Harpoon	NA	NA	NA	NA	NA	NA	53.8 b	55.5 ab	56.7 a	52.8 b	55.6 a	55.9 a	55.0 DEF
SRW9606	NA	NA	NA	NA	NA	NA	53.3 a	55.2 a	56.5 a	51.3 c	54.1 b	55.8 a	54.3 F
AVERAGE†	57.3 b	58.4 a	58.6 a	53.7 b	56.1 a	56.6 a	55.6 b	57.8 a	58.6 a	53.2 b	55.8 a	56.2 a	

*Variety average across all years. Letters in this column denote Tukey HSD groups of significant differences (α = 0.05) in average yield due to variety. † Average test weight across all varieties. Letters in this row denote significant differences in test weight due to management intensity across all yields.

Table 4. Frequency of price deductions within each management intensity category, based on 122 total observations for each management category.

Deduction categories†	Current	Mid-level	High-level
No test weight deduction	13.84%	37.05%	43.30%
$0.08 USD test weight deduction	21.88%	30.80%	28.13%
$0.10 USD test weight deduction	50.89%	31.70%	28.57%
$0.12 USD test weight deduction	13.39%	0.45%	0.00%
No DON deduction	80.36%	100.00%	99.11%
$0.20 DON deduction	16.96%	0.00%	0.89%
$0.30 DON deduction	1.79%	0.00%	0.00%
DON Rejection	0.89%	0.00%	0.00%

† Deduction categories based on information in Supplemental File 1.

Table 5. Estimated costs and profits associated with each management intensity level.

	Current	Mid-level	High-level
Profit potential of grain and straw produced ($USD per acre)	$569.00	$678.00	$709.00
Estimated cost of management ($USD per acre)	$77.98	$138.09	$206.01
Probability of a deduction†	88.88%	62.95%	57.08%
Net profit ($USD per acre)	**$140.01**	**$263.90**	**$238.07**

† Probabilities based on the frequency of observed plots that met the criteria for a deduction according to 2018 Wheat Discount and Storage Schedule of the Landmark Services Cooperative.

Increasing management intensity has a higher return on investment

Although increasing management intensity is associated with increased cost, it is also associated with increased grain yield, increased straw yield, decreased disease, and decreased grain price deduction frequencies (Table 4). To determine if these benefits are also profitable, the profit potential per acre was estimated using fixed prices of grain and straw, taking costs of management products, applications, and frequencies of price deductions into consideration. This culminated in an estimated net profit per acre for each management intensity in this study. At a fixed grain value of $5 per bushel of wheat and a fixed straw value of $100 per ton, the mid-level management intensity had the highest net profit, followed by the high-level and the current strategies, respectively (Table 5). The mid-level management strategy netted $124 more per acre than the current strategy, and the high-level management strategy netted $98 more per acre than the current strategy.

CONCLUSIONS

Wheat production recommendations have changed greatly in recent years due to our increasing understanding of nutrient applications, fungicide use, and timing. Still, wheat production faces many emerging challenges, such as severe disease outbreaks and increasing frequency of extreme weather events. Additionally, increasing costs of land and diminishing profit margins have made farming as economically challenging as ever.

This study was initiated to ensure that appropriate recommendations can be made to wheat growers to produce an economically viable crop in a sustainable manner. A properly managed crop will benefit the food supply and human nutrition, while managing wheat diseases and maximizing yields can provide financial stability to Midwest farms, particularly if wheat acreage continues to decline. Based on the results provided in this study, the mid-level management strategy appears to be the most appealing financially, with the highest return on investment of $263.90 USD per acre. The high-level management resulted in a lower net profit of $238.07 USD per acre, but was the only management strategy to significantly reduce stripe rust, so the additional fungicide spray in this strategy may be appealing to farmers concerned about stripe rust outbreaks. Both mid- and high-level managements were more profitable than the average net profit of $140.01 USD per acre produced by the current management strategy. By adopting the mid-level management strategy and monitoring for stripe rust outbreaks, Wisconsin winter wheat farmers can increase yields and returns on their investment to produce high-yielding and profitable wheat.

ACKNOWLEDGEMENTS

REFERENCES

Beddow, J.M., P.G. Pardey, Y. Chai, T.M. Hurley, D.J. Kriticos, H.-J. Braun, R.F. Park, W.S. Cuddy, and T. Yonow. 2015. Research investment implications of shifts in the global geography of wheat stripe rust. Nat. Plants 1:15132.

Cakmak, I. 2009. Enrichment of fertilizers with zinc: an excellent investment for humanity and crop production in India. J. Trace Elements Med. Biol. 29:281-289.

Chen, X.M. 2014. Integration of cultivar resistance and fungicide application for control of wheat stripe rust. Can. J. Plant Pathol. 36:311-326.

Chen, X., and Z. Kang. 2017. Integrated control of stripe rust. In: Chen X., Kang Z. (eds) Stripe Rust. Springer, Dordrecht, Netherlands. doi: 10.1007/978-94-024-1111-9_6.

da Silva, C.L., A. Fritz, M. Clinesmith, J. Poland, F. Dowell, and K. Peiris, 2019. QTL mapping of Fusarium head blight resistance and deoxynivalenol accumulation in the Kansas wheat variety 'Everest'. Mol. Breed. 39:35.

de Oliveira Silva, A., G.A. Slafer, A.K. Fritz, and R.P. Lollato. 2020. Physiological basis of genotypic response to management in dryland wheat. Front. Plant Sci. 10:1644.

Dimkpa, C.O., and P.S. Bindraban. 2016. Fortification of micronutrients for efficient agronomic production: a review. Agron. Sustain. Dev. 36:7.

Figueroa, M., K.E. Hammond-Kosack, and P.S. Solomon. 2018. A review of wheat diseases - a field perspective. Mol. Plant Pathol. 19:1523-1536.

Gilbert, J., and S. Haber. 2013. Overview of some recent research developments in Fusarium head blight of wheat. Can. J. Plant Pathol. 35:149-174.

Herrera, J.M., L.L. Häner, F. Mascher, J. Hiltbrunner, D. Fossati, C. Brabant, R. Charles, and D. Pellet. 2020. Lessons from 20 years of studies of wheat genotypes in multiple environments and under contrasting production systems. Front. Plant Sci. 10:1745.

Jaenisch, B.R., A. de Oliveira Silva, E. DeWolf, D.A. Ruiz-Diaz. and R.P. Lollato. 2019. Plant population and fungicide economically reduced winter wheat yield gap in Kansas. Agron. J. 111:650-665.

Kelly, J.T., R.K. Bacon, and E.E. Gbur. 1995. Relationship of grain yield and test weight in soft red winter wheat. Cereal Res. Commun. 23:53-57.

Laboski, C.A.M., and J.B. Peters. 2012. Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin (A2809). Retrieved from https://walworth.extension.wisc.edu/files/2018/11/Nutrient-Application-Guidelines-for-Field-Vegetable-Fruit-Crops-in-WI-A2809.pdf.

Large, E.C. 1954. Growth stages in cereals illustration of the Feekes scale. Plant Pathol. 3:128-129.

Lollato, R.P., D.A. Ruiz Diaz, E. DeWolf, M. Knapp, D.E. Peterson, and A.K. Fritz. 2019. Agronomic practices for reducing wheat yield gaps: a quantitative appraisal of progressive producers. Crop Sci. 59: 333-350.

Lollato, R.P., K. Roozeboom, J.F. Lingenfelser, C. Lemes da Silva, and G. Sassenrath. 2020. Soft winter wheat outyields hard winter wheat in a subhumid environment: Weather drivers, yield plasticity, and rates of yield gain. Crop Sci. 60:1617-1633.

McMullen, M., G. Bergstrom, E. De Wolf, R. Dill-Macky, D. Hershman, G. Shaner, and D. Van Sanford. 2012. A unified effort to fight an enemy of wheat and barley: Fusarium head blight. Plant Dis. 96:1712-1728.

Mueller, B.D., C.L. Groves, S.P. Conley, S.A. Chapman, M. Kabbage, and D.L. Smith. 2020. Integrated management of stripe rust and overwintering of *Puccinia striiformis* f. sp. *tritici* in Wisconsin. Plant Health Prog. 21:205-211.

Nishio, Z., K. Takata, M. Ito, M. Tanio, T. Tabiki, H. Yamauchi, and T. Ban. 2010. Deoxynivalenol distribution in flour and bran of spring wheat lines with different levels of Fusarium head blight resistance. Plant Dis. 94:335-338.

Oliver, R.P. 2014. A reassessment of the risk of rust fungi developing resistance to fungicides. Pest Manag. Sci. 70:1641-1645.

Paul, P.A., P.E. Lipps, D.E. Hershman, M.P. McMullen, M.A. Draper, and L.V. Madden. 2008. Efficacy of triazole-based fungicides for Fusarium head blight and deoxynivalenol control in wheat: a multivariate meta-analysis. Phytopathology. 98:999-1011.

Pestka, J.J. 2007. Deoxynivalenol: Toxicity, mechanisms and animal health risks. Anim. Feed Sci. Technol. 137:283-298.

Pirgozliev, S.R., R. V. Ray, S.G. Edwards, M.C. Hare, and P. Jenkinson. 2008. Effect of timing of fungicide application on the development of Fusarium head blight and the accumulation of deoxynivalenol (DON) in winter wheat grain. Cereal Res. Commun. 36:289-299.

Plastina, A. 2020. Estimated costs of crop production in Iowa - 2020. p. 12. https://store.extension.iastate.edu/Product/fm1712-pdf.

Quinn, D. and K. Steinke. 2019. Soft red and white winter wheat response to input-intensive management. Agron. J. 111:428-439.

Rietra, R.P.J.J., M. Heinen, C.O. Dimkpa, and P.S. Bindraban. 2017. Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. Commun. Soil Sci. Plant Anal. 48:1895-1920.

Salgado, J.D., L.V. Madden, and P.A. Paul. 2015. Quantifying the effects of Fusarium head blight on grain yield and test weight in soft red winter wheat. Phytopathology 105:295-306.

Schwessinger, B. 2017. Fundamental wheat stripe rust research in the 21st century. New Phytol. 213:1625-1631.

(USDA) U.S. Department of Agriculture National Agricultural Statistics Service (NASS). 2020. Quick Stats. USDA, Beltsville, MD.

Wang, S., M. Li, X. Tian, J. Li, H. Li, Y. Ni, J. Zhao, Y. Chen, C. Guo, and A. Zhao. 2015. Foliar zinc, nitrogen, and phosphorus application effects on micronutrient concentrations in winter wheat. Agron. J. 107:61-70.