ADF Project # 20170205:

Improved Integrated Disease Management for Oats (*Avena sativa* L.) in Saskatchewan

Compiled by:

Christiane Catellier[1] & Jessica (Pratchler) Slowski[2]

[1]Indian Head Agricultural Research Foundation (IHARF), P.O. Box 156, Indian Head, SK. S0G 2K0
[2]Northeast Agriculture Research Foundation (NARF), P.O. Box 1240 Melfort, SK. S0E 1A0

Principal Investigator:

Jessica (Pratchler) Slowski[2]

Collaborators:

Brianne McInnes[2], Michael Hall[3], Chris Holzapfel[1], Lana Shaw[4]

[3] East Central Research Foundation, PO Box 1939 Yorkton, SK S3N 3X3
[4] South East Research Farm, PO Box 129 Redvers, SK S0C 2H0

Correspondence:

Brianne McInnes[2]

November 30, 2021

Final Report

ABSTRACT

Studies on integrated disease management (IDM) have shown that utilizing several management practices simultaneously is often most effective for disease control in crops. In oats (*Avena sativa* L.), the efficacy of fungicide application for preserving oat yield and quality has been shown to vary with varietal disease resistance. Further, studies have suggested that increasing the seeding rate can be effective in reducing tillering in cereals, subsequently resulting in more uniform crop development and better fungicide application timing and efficacy for head disease but thicker crop canopies which could increase leaf disease. Thus, the objectives of this study were to assess the integration of genetic disease resistance, seeding rate, and fungicide application timing for disease management in oats. A small plot research study was conducted at Indian Head, Melfort, Redvers, and Yorkton, Saskatchewan in 2018, 2019, and 2020. A randomized split-plot design was utilized with fungicide timing (Untreated, Flag leaf, Heading) as the main plot, and variety (CS Camden, Summit) and seeding rate (300 or 450 seeds/m^2) as sub-plots. The 12 treatments were each replicated four times at each location in each year. Conditions were not highly conducive to disease development at any of the locations or years of the study. Effects of variety, seeding rate, and fungicide were all dependent on environments. There were often variety by seeding rate interactions, but seeding rate and variety effects were nearly always independent of fungicide treatments. Effects of fungicide application were inconsistent and often inconclusive, as untreated treatments performed as well as either of the fungicide application timings, even when there were significant differences between the treatments. Fungicide effects and interactions with variety or seeding rate would likely have been more frequent and consistent if environmental conditions had been conducive to disease development. It is recommended that producers continue to combine several practices to manage disease in oats, as the effects can be additive, if not interactive. The effectiveness of applying fungicide for disease management did not appear to vary with varieties or seeding rates in this study. Thus, the decision to apply fungicide, and at what timing, should be based on environmental conditions being conducive to disease development.

INTRODUCTION

The Canadian Prairies produce most of North America's oats destined for human consumption. Eastern Saskatchewan is one of the major oat growing regions in Canada and production is largely concentrated in crop districts 5, 6, 8, and 9. Currently, most of Saskatchewan's production is sold into the milling market, making quality a top priority.

The main oat growing regions in Saskatchewan generally receive more moisture than other areas of the province and are associated with a greater risk of disease development. Higher moisture conditions are conducive for the development of head and other leaf diseases such as *Pyrenophora* Leaf Blotch, *Stagonospora* Leaf Blotch (May et al. 2014), and *Septoria* Leaf Blotch Complex. These leaf diseases are of concern throughout the oat growing regions but are more prominent in northernly growing regions. Little is known about the impact of these leaf diseases on yield, quality, and the economics of oat production throughout the region. Oat Stem Rust and Oat Crown Rust occur infrequently but have historically resulted in severe economic losses for oat production when outbreaks occur (Fetch et al. 2011, McCalumm et al. 2007). Southern portions of Saskatchewan are particularly prone to Oat Crown Rust because the rust pathogen overwinters in the United States and moves northward with air currents. Rust spores usually reach significant levels in the Canadian Prairies during June (McCallum et al. 2007), and gradually moves further northward as the growing season progresses. The risk of yield and quality losses increase with earlier movement and development of Oat Crown Rust inoculum. Fusarium Head Blight (FHB) is not currently a major downgrading factor in oat, but symptoms are frequently noted when conditions are favourable for this disease. As FHB causes significant yield and quality losses in other cereals, producers question the implications of this disease for oat production in the same growing regions.

Management practices for disease control in oats include fungicide application and utilizing resistant varieties (McCallum et al. 2007). In Canada, Crown Rust-resistant varieties are available, but genetic resistance to Oat Stem Rust is limited. Resistant cultivars have been shown to be effective in reducing yield losses, however the efficacy of genetic resistance is reduced as the pathogens evolve. For this reason, industry agronomists commonly recommend preventative fungicide applications in combination with resistant varieties. Furthermore, little is known about the varietal differences in resistance to Septoria Leaf Blotch complex and Fusarium Head Blight. Although genetic resistance is highly beneficial, selection of other traits for agronomic purposes (lodging, test weight) might be of higher priority for growers. Consequently, when varieties are selected for agronomic traits, there may be an increase reliance on fungicides for disease control.

Triazole fungicides, including Tilt (propiconazole) and Folicur (Tebuconazole), have been shown to be effective at controlling rust diseases, as well as Fusarium Head Blight (McCallum et al. 2007; Picinini and Fernandes 1994). The optimal timing for control of rust and leaf diseases is at the flag leaf stage (Zadoks 39) (Bowen et al 2016). This differs from the optimal application timing for the control of head diseases, which is typically after head emergence. In addition, the late onset of Crown Rust in northern areas suggests the optimal fungicide application may be later in this area than traditionally recommended in more southern regions. Studies documenting yield and/or quality improvements from fungicidal control of Septoria Leaf Blotch complex are limited.

Studies on integrated disease management (IDM) have shown that utilizing several management practices simultaneously is often most effective for disease control in crops. In oats, the efficacy of fungicide application for preserving oat yield and quality has been shown to vary with varietal disease resistance. May et al. (2014) found that, under high disease pressure, varieties rated as susceptible to Oat Crown Rust consistently showed greater yields and test weights with fungicide application. Other quality factors such as B-glucan levels were less impacted by fungicide application and were more responsive to seeding date and varietal selection. Varieties with genetic resistance for Crown Rust did not benefit from fungicide application. Soovali and Koppel (2011) found that, under low leaf spot disease pressure, fungicide application at flag leaf timing provided significant disease control, while applications at heading only provided significant results for certain varieties and under higher disease pressure. Furthermore, studies have suggested that increasing the seeding rate can be effective in reducing tillering in cereals. Reduced tillering results in more uniform crop development, allowing producers to improve application timing, and subsequently improve fungicide efficacy. To our knowledge, there are no studies combining seeding rate, fungicide use, and genetic resistance for oat disease management.

Growers across Saskatchewan have identified a need for further investigation into integrated disease management in oats. To preserve the effectiveness of genetic and fungicidal disease control measures, fungicides should only be applied if they provide agronomic and economic benefits. This will require a better understanding of how various management tools interact and can be integrated together for disease management in oats. This study will assess the integration of genetic disease resistance, seeding rates, and fungicide application timing for disease control in oats.

METHODOLOGY

Study design

A small plot research study was conducted with field trials at Indian Head, Melfort, Redvers, and Yorkton, Saskatchewan in 2018, 2019, and 2020. The four locations are representative of the various soil and climatic conditions found within the major oat growing region of the province. The treatments were laid out in a randomized split-plot design with fungicide timing as the main plot and variety and seeding rate fully randomized within the sub-plots. There were three fungicide application timing treatments: Untreated, Flag Leaf, and Heading. The four variety and seeding rate treatments consisted of two milling oat varieties, CS Camden and Summit, which differ in yield potential, lodging, and disease resistance, sown at two different seeding rates. The seeding rates were 1x (300 seeds/m^2) and 1.5x (450 seeds/m^2) of the recommended seeding rate for oats. Together, the treatments were combined to develop a 3 by 4 split plot factorial study with a total of 12 treatments (Table 1). Each treatment was replicated 4 times at each location in each year.

Table 1. The list of treatments assessed at four locations over four years. Fungicide timing was the main split-plot and was randomized within replicates. Varieties and seeding rates were fully randomized within each of the fungicide treatments.

Treatment	Fungicide Timing	Variety	Seeding rate (seeds m^{-2})
1	Untreated	CS Camden	300
2			450
3		Summit	300
4			450
5	Flag Leaf	CS Camden	300
6			450
7		Summit	300
8			450
9	Heading	CS Camden	300
10			450
11		Summit	300
12			450

Field operations and data collection

All sites were seeded between May 4 and May 23, with later seeding dates in general at Melfort (Table A-1). Plot sizes varied between locations due to equipment differences, with a minimum plot size of 2m by 6m. Row spacing varied between locations, with Melfort, Indian Head, and Yorkton using 30.5 cm row spacing, and Redvers using 25.4 cm. The trials were seeded into either oilseed or pulse stubble, between 2.5 to 4 cm deep. Seeding rates for each seed lot at each location were corrected for the germination (%) and seed weight (g/1000 seeds). A seeding rate error at Redvers in 2019 resulted in excessively low seeding rates for all treatments, and a seeding rate error at Yorkton in 2020 resulted in the 450 seeds/m^2 seeding rate treatments being seeded at 375 seeds/m^2. In most cases, seeding and fertilization were completed in the same operation. All fertilizer applied was based on soil test recommendations to target a 150 bu/ac oat crop. The total amount of nitrogen applied was balanced for the nitrogen provided by other fertilizers.

Following the treatment protocol, Caramba foliar fungicide (metconazole) was applied either at the flag leaf stage (Zadoks 39) at the recommended rate (280 mL/ac), or at the heading stage (Zadoks 59) at the recommended rate (400 mL/ac), with a water volume of 40 L/ac (application dates shown in Table A-1). General applications of pre-seed and in-crop herbicide were site dependent to ensure non-limiting yield conditions were met (Table A-2). A spraying error at Redvers in 2019 resulted in all plots of several treatments being terminated. Insecticide and pre-harvest applications were not required at any location in any year. Harvest dates are shown in Table A-1.

Data collection included plant density, tiller density, panicle density, disease ratings, lodging, maturity, yield, kernel weight, grain milling quality, and seed-borne disease. Plant density was determined by counting the number of oat seedlings along two 1-meter sections of crop row per plot. Tiller density was determined by the destructive sampling of two 0.5-m sections, in the same location as plant density counts, and counting the number of tillers on each plant. Panicle density was determined by counting the number of panicles in two 0.5-m sections of crop row per plot. The number of tillers per plant and panicles per plant were calculated using plant density values from each plot. Rust and leaf spot disease ratings were completed by collecting 10 flag and penultimate leaves, prior to each fungicide application, and at the Milk stage. Crown and Stem Rust were rated using the Cobb Scale (1-100) (Table A-3). Leaf spot diseases were rated using the Horsfall-Barratt scale (1-12) (Table A-4). The Horsfall-Baratt scale is based on ratings from 1-12, which are then transformed to a disease severity index (DSI) which is reported as a percentage. Prior to maturity, the percentage of the plot displaying Fusarium Head Blight symptoms was recorded to measure FHB severity. Lodging severity was rated for each plot using the Belgian Lodging scale (area affected [1-9] X intensity [1-5] X 0.2). Maturity was recorded on a relative scale, at the first detection of dry down, with 1 recorded as advanced maturity, 2 as average, and 3 as delayed dry down or maturity. Oat grain yield was determined from a cleaned, weighed sample, and adjusted to 13% moisture content. Quality measurements consisted of thousand kernel weight (TKW), Beta-glucan, plump, thins, groat, protein, and seed-borne diseases. TKW was determined using CGC methodology. A 500g sub-sample from each plot was submitted to General Mills for protein, plump, thin, groat, and Beta-glucan analysis. Protein and Beta-Glucan were measured using NIR. Plump kernels were determined from the mass of a 100g sample that remained on the top of a 5.5 X 64 slotted screen after being shaken 30 times. What passed through the previous and an additional 5.0 by 64 slotted screen was weighed to determine the proportion of thin kernels. The percent groat was calculated based on the total amount of groat recovered after aspiration of the sample. A separate 500g sub-sample was submitted to Seed Solution Seed Labs in Swift Current for seed-borne disease analysis including the percentage of all *Fusarium* species, *Alternaria* species, and *Cochliobolus sativus.*

Statistical analysis

Data were analyzed with the R statistical program, version 4.0.4 (R Core Team 2021), using the *lme4* package (Bates et al. 2015) for fitting mixed-effects models, the *lmerTest* package (Kuznetsova et al. 2017) for assessing model fit and treatment differences, and the *emmeans* package (Length 2021) for means separation. Data from all site-years were combined for a multi-site analysis. To assess the overall response across environments, mixed effects models were fitted for each response variable with variety, seeding rate, fungicide treatment, all two-way interactions, and the three-way interaction as fixed effects, and site-year, replicate within site-year, and fungicide (main split-plot) within replicate within site-year as random effects. Then, to determine the presence of significant site-year interactions, mixed effects models were fitted with site-year, variety, seeding rate, fungicide, all two- and three-way interactions, and the four-way interaction as fixed effects, and replicate within site-year and fungicide (main split-plot) within replicate within site-year as random effects. If significant site-year interactions were identified, then site-years were analyzed individually, with only the treatment variables with significant site-year interactions as fixed effects, and replicate and fungicide within replicate as random effects. Treatment effects and interactions at individual site-years were not discussed when there were no significant site-year interactions. Fungicide and interactions with fungicide were not included as fixed effects for plant density and tillering. Seed quality variables (protein, plumps, thins, groat, and B-glucan) were measured on a composite basis, providing only one replicate per treatment per site-year, thus site-year interactions were not assessed for these variables. Response variables were transformed as needed to meet the assumptions of normality and homogeneity of variance of the model residuals. Estimated marginal means were separated using the Tukey method for multiple comparisons adjustment and alpha = 0.05.

Soil and weather conditions

Indian Head and Yorkton are situated in the Thin Black soil zone, Melfort is in the Thick Black soil zone, and Redvers is in the Dark Brown soil zone. In general, Melfort soils have very high organic matter, Yorkton has high organic matter, and Indian Head and Redvers have medium organic matter. Indian Head, Yorkton, and Redvers have alkaline soils, while Melfort soils are acidic.

Prior to seeding each trial area, the location was soil sampled to determine residual soil nutrient levels (Table 2). Residual soil nitrates ranged from a low of 14 lb/ac at Indian Head in 2018 to a high of 60 lb/ac at Yorkton in 2020. Residual soil phosphorus ranged from 3-19 ppm across site-years. Residual potassium was high across all site-years. Residual sulfur ranged widely from 29 lb/ac at Indian Head in 2019 to 178 lb/ac at Yorkton in 2019.

Table 2. Residual soil nutrient levels at the 0 – 24” depth for N (NO_3-N) and S, and 0 – 6” depth for all other nutrients and soil attributes at four locations and in three years included in the study.

Location	N (lb/ac)	P (Olsen, ppm)	K (ppm)	S (lb/ac)	OM (%)	pH
			2018			
Indian Head	14	5	614	72	5.1	7.6
Melfort	20	7	364	54	8.5	6.2
Redvers	47	4	264	120	3.1	7.8
Yorkton	24	14	373	134	6.4	7.1
			2019			
Indian Head	43	6	589	29	5.6	7.5
Melfort	19	15	500	68	9.4	5.9
Redvers	47	3	223	74	3.8	8.0
Yorkton	32	15	482	178	7.0	7.7
			2020			
Indian Head	21	3	560	80	5.5	7.7
Melfort	54	19	477	48	9	6.3
Redvers						
Yorkton	60	10	266	78	5.7	7.2

Average monthly temperatures over the growing season are summarized in Table 3 and precipitation is summarized in Table 4 for each site-year, along with climate normals for each location. Growing season temperatures were generally close to average across all site-years, apart from warmer than average conditions in May 2018, and cooler than average conditions in April 2018 and 2020, May 2019, and August 2019. Early season (April to July) precipitation was lower than normal in all years at Indian Head and Yorkton, and in Melfort 2018, while Melfort 2019 and 2020 and Redvers were closer to average. Soil moisture was replenished in fall 2019 at Indian Head but not Yorkton, thus conditions at Yorkton in 2020 were very dry. Yorkton also experienced hotter than normal conditions in July 2020.

Table 3. Actual average monthly temperatures at each location and year of the study, and normal (1981-2010) average monthly temperature at each location over the growing season. IC=Incomplete record.

Location	April	May	June	July	August	September
Indian Head						
2018	-2.1	13.9	16.5	17.5	17.6	7.6
2019	3.9	8.9	15.7	17.4	15.8	11.9
2020	0.3	10.7	15.6	18.4	17.9	11.5
Normal	4.2	10.8	15.8	18.2	17.4	11.5
Melfort						
2018	-3.4	13.9	16.8	17.5	15.9	6.9
2019	3.0	8.8	15.3	16.9	14.9	11.2
2020	-2.9	10.1	14.3	18.8	17.6	10.8
Normal	2.8	10.7	15.9	17.5	16.8	10.8
Redvers (Oxbow)						
2018	-1.2	14.4	17.6	19.2	IC	10.2
2020	1.3	10.3	17.3	19.4	19.4	12.7
Normal	-	11.1	16.2	18.7	18.0	12.5
Yorkton						
2018	-2.4	14.8	17.4	18.5	17.0	8.0
2019	3.9	7.8	16.1	18.2	15.9	12.0
2020	-0.2	10.2	16.2	19.7	18.1	11.0
Normal	3.2	10.4	15.5	17.9	17.1	11.1

Table 4. Actual total monthly precipitation at each location and year of the study, and normal (1981-2010) monthly precipitation at each location over the growing season. IC=Incomplete record.

Location	April	May	June	July	August	September
Indian Head						
2018	8.5	23.7	90.0	30.4	3.9	39.6
2019	25.3	13.3	50.4	53.1	96.0	120.8
2020	22.0	27.3	23.5	37.7	24.9	15.0
Normal	22.6	51.7	77.4	63.8	51.2	35.3
Melfort						
2018	5.0	38.5	46.6	69.5	43.2	42.0
2019	4.1	18.8	87.4	72.7	30.7	43.0
2020	11.1	26.7	103.7	52.4	18.5	21.2
Normal	26.7	42.9	54.3	76.7	52.4	38.7
Redvers (Oxbow)						
2018	4.0	28.5	194.4	40.2	IC	55.2
2020	9.0	31.0	118.5	45.4	22.2	6.8
Normal	-	60.0	95.2	65.5	46.6	32.7
Yorkton						
2018	4.1	14.0	117.3	58.3	31.5	59.9
2019	17.6	11.3	75.6	49.9	31.0	53.6
2020	10.3	17.2	31.7	78.0	48.5	27.4
Normal	21.6	51.3	80.1	78.2	62.2	44.9

RESULTS

Not all measurements were completed at each site-year. Redvers 2019 was removed from all analyses due to unreliable data resulting from technical issues during both seeding and spraying operations. When averaged across site-years, variety, seeding rate, and fungicide treatments all had significant effects on several crop response variables, however significant interactions were only found with variety and seeding rate for two of the variables (Table 5). There were site-year interactions with variety for all the crop response variables, with seeding rate or fungicide for several variables, and there was a three-way interaction with variety and seeding rate for a few variables, but there were no other significant three-way interactions and the four-way interaction was also not significant (Table 6).

Table 5. F-test results of mixed-effects model analysis of the crop response variables, with site-year included as a random effect, to assess the overall effect of each treatment and interactions of the treatments across site-years. Effects are considered statistically significant if P≤0.05.

	Plant density	Tillers per plant	Panicles per plant	Lodging	Maturity	Yield	TKW
Variety (V)	0.310	**0.017**	**<0.001**	**<0.001**	**<0.001**	0.852	**<0.001**
Seeding Rate (R)	**<0.001**	**<0.001**	**<0.001**	**0.004**	0.095	**0.002**	0.431
Fungicide (F)	-	-	**0.008**	0.182	**0.032**	**0.013**	0.377
V X R	0.221	**0.006**	0.190	**0.039**	0.641	0.806	0.449
V X F	-	-	0.439	0.174	0.956	0.533	0.820
R X F	-	-	0.986	0.735	0.796	0.535	0.688
V X R X F	-	-	0.846	0.519	0.231	0.343	0.326

Table 6. F-test results of mixed-effects model analysis of the crop response variables, with site-year included as a fixed effect, to assess the presence of site-year interactions with each treatment and factorial combination of treatments. Effects are considered statistically significant if Pv0.05.

	Plant density	Tillers per plant	Panicles per plant	Lodging	Maturity	Yield	TKW
Variety (V)	0.230	**0.007**	**<0.001**	**<0.001**	**<0.001**	0.861	**<0.001**
Seeding Rate (R)	**<0.001**	**<0.001**	**<0.001**	**0.001**	**0.021**	**0.002**	0.391
Fungicide (F)	-	-	**0.008**	0.101	**0.001**	**0.001**	0.328
Site-year (S)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**
V X R	0.147	**0.002**	0.182	**0.019**	0.520	0.815	0.409
V X F	-	-	0.438	0.103	0.918	0.518	0.810
R X F	-	-	0.987	0.668	0.647	0.540	0.665
V X S	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
R X S	**<0.001**	**<0.001**	0.336	**0.004**	**<0.001**	0.390	**0.002**
F X S	-	-	0.150	**0.013**	**<0.001**	**<0.001**	0.071
V X R X F	-	-	0.834	0.424	0.062	0.343	0.311
V X R X S	**<0.001**	**0.007**	0.336	**0.008**	**0.006**	0.811	0.782
V X F X S	-	-	0.988	0.306	0.943	0.999	0.445
R X F X S	-	-	0.998	0.364	0.152	0.983	0.560
V X R X F X S	-	-	0.966	0.911	0.567	0.971	0.830

Plant density

Ten site-years were included in the plant density analysis. Extreme dry conditions in Melfort in 2019 resulted in delayed emergence and low plant populations at the time of assessment, so this site-year was not included in the plant density analysis. Significant emergence occurred following June precipitation and the plant populations recovered, so the site-year was retained in the analysis of other variables.

Averaged across site-years, plant density differed significantly between seeding rates but was not affected by variety, and the interaction between seeding rate and variety was not significant (Table 5). The seeding rate effect was as expected, where overall plant density was significantly lower at the 300 seeds/m^2 rate (285 plants/m^2 ± 9.57) than at the 450 seeds/m^2 rate (381 plants/m^2 ± 9.57). However, there were significant site-year interactions with variety and seeding rate (Table 6). When site-years were analyzed individually, three site-years had only the significant seeding rate effect (Figure 1). At four site-years, there was also a difference in plant density between varieties; at Indian Head in all three years, Camden had significantly higher plant density than Summit, while at Yorkton in 2018, Summit had significantly higher plant density. There was a variety by seeding rate interaction at three site-years, indicating that the seeding rate effect was more pronounced in one variety than the other, but that was not consistently the same variety at these three site-years. Seeding rate was expected to affect plant density but variety was not, considering the seeding rates were corrected for germination and seed weight of each seed lot separately. In general, however, the high and low seeding rates resulted in high and low plant densities within varieties at each site-year, apart from Melfort 2018 where plant density did not differ between the two seeding rates for Camden.

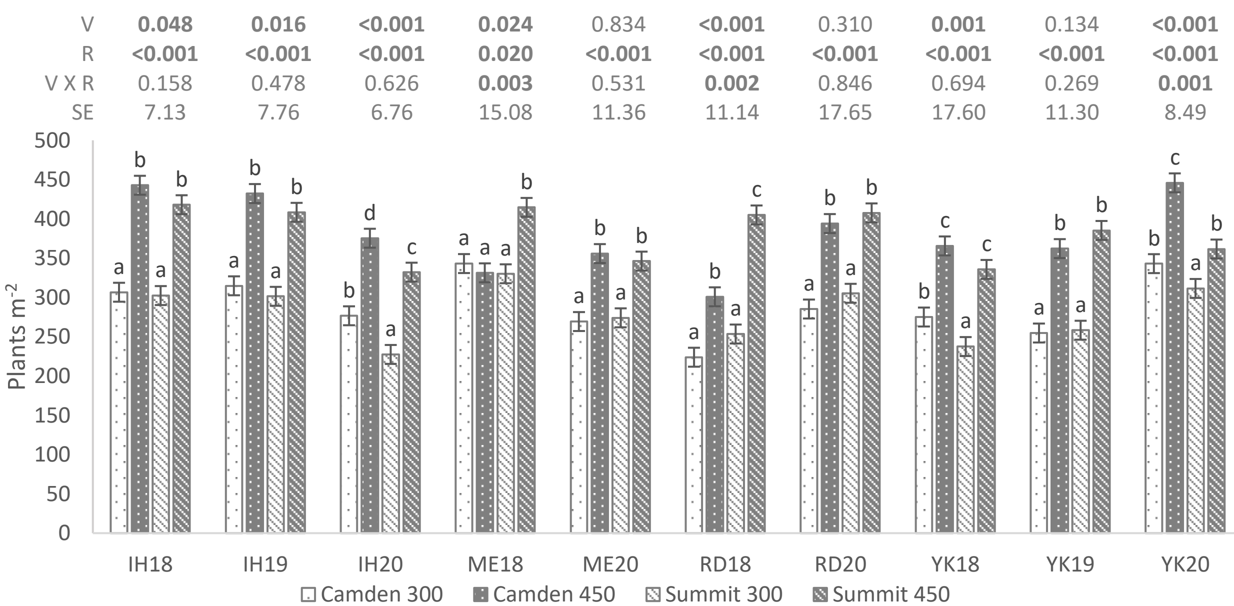

Figure 1. The effect of variety (V) and seeding rate (R) and their interaction (V X R) on plant density at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P<0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Tiller and panicle development

Tiller density was not recorded at Indian Head in any year, or in Redvers in 2020, leaving 7 site-years of data. The number of tillers per plant (TPP) was calculated using the spring plant density values. The TPP was square-root transformed.

Averaged across site-years, the number of tillers per plant was significantly affected by variety and seeding rate, and there was a significant interaction between variety and seeding rate (Table 5). The interaction was such that there was no difference between seeding rates with Camden, but there were significantly more tillers per plant at the lower seeding rate with Summit (Figure 2). Again, there were significant site-year interactions with variety and seeding rate (Table 6). When site-years were analyzed individually, there was no significant effects at one site-year, significant effects of both variety and seeding rate at five site-years, and a significant variety by seeding rate interaction at one site-year (Figure 3). In the five site-years with both variety and seeding rate effects, the lower seeding rate consistently resulted in a greater number of tillers per plant, but the variety effect was not consistent across site-years, though Summit more often had a greater number of tillers per plant than Camden. The variety by seeding rate interaction at Melfort in 2019 was consistent with the overall interaction across site-years, where the lower seeding rate did not result in significantly more tillering for Camden. In general, seeding rate appeared to have a greater effect on tillering than variety.

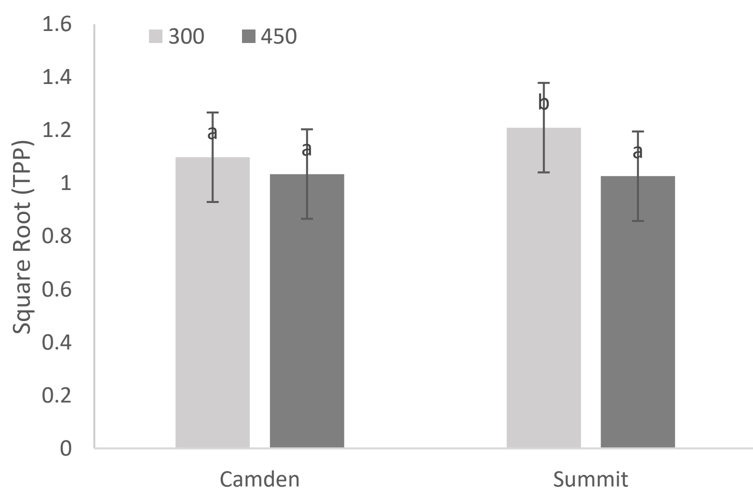

Figure 2. The interaction of variety and seeding rate on the number of tillers per plant across all site-years. Error bars indicate the standard error. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

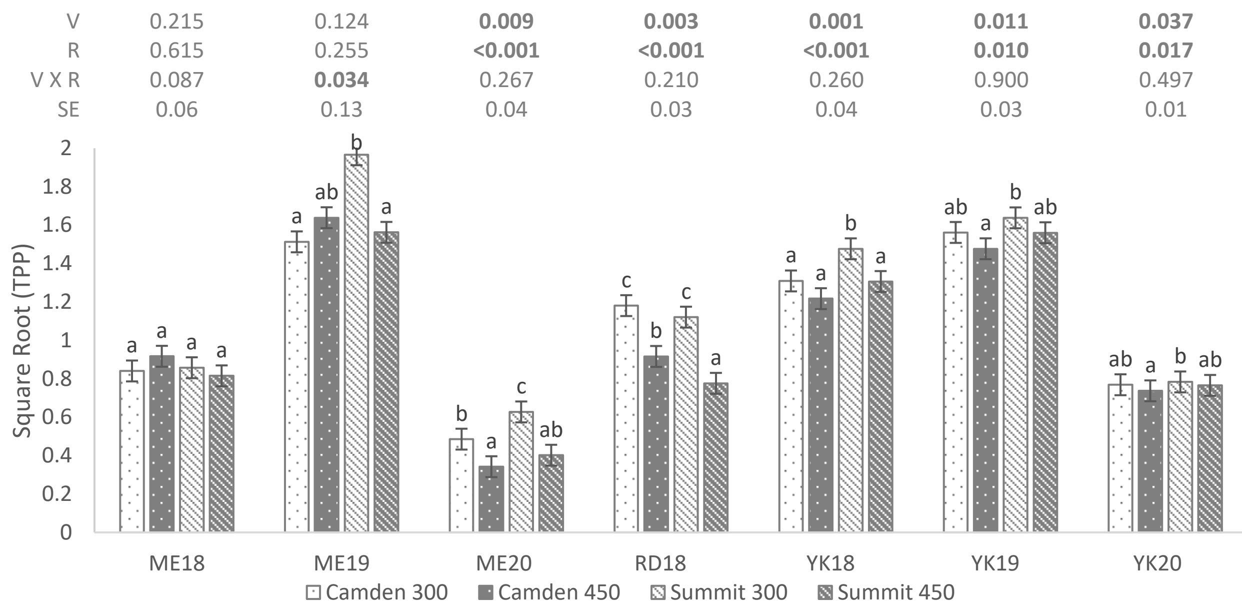

Figure 3. The effect of variety (V) and seeding rate (R) and their interaction (V X R) on tillers per plant at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P<0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Panicle density was not recorded at Redvers and Yorkton in 2018, nor at Melfort in 2018 and 2020, leaving 7 site-years of data. The number of panicles per plant (PPP) was calculated using the spring plant density values. The PPP was log-transformed.

Averaged across site-years, the number of panicles per plant was significantly affected by variety, seeding rate, and fungicide treatment, but there were no significant interactions (Table 5). Overall, the number of panicles per plant was significantly higher Summit than Camden, significantly higher at the 300 seeds/m^2 rate than the 450 seeds/m^2 rate, and significantly lower when fungicide was not applied than when fungicide was applied (**Table 7**). The effect of variety and seeding rate were consistent with the effect on the number of tillers, but the fungicide effect is unexpected as the development of the panicles would have been expected to be set prior to fungicide application. There was a site-year interaction with variety only (Table 6). When site-years were analyzed individually, there were significantly more panicles per plant with Summit than with Camden at five site-years, but no significant difference between varieties at two of the site-years (Figure 4).

Table 7. The effect of variety, seeding rate, and fungicide treatment on the number of panicles per plant across all site-years. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

Effect	Treatment	
Variety	Camden	0.11 a
	Summit	0.27 b
	SE	0.04
Seeding Rate	300	0.25 b
	450	0.15 a
	SE	0.04
Fungicide	Untreated	0.14 a
	Flag Leaf	0.22 b
	Heading	0.22 b
	SE	0.04

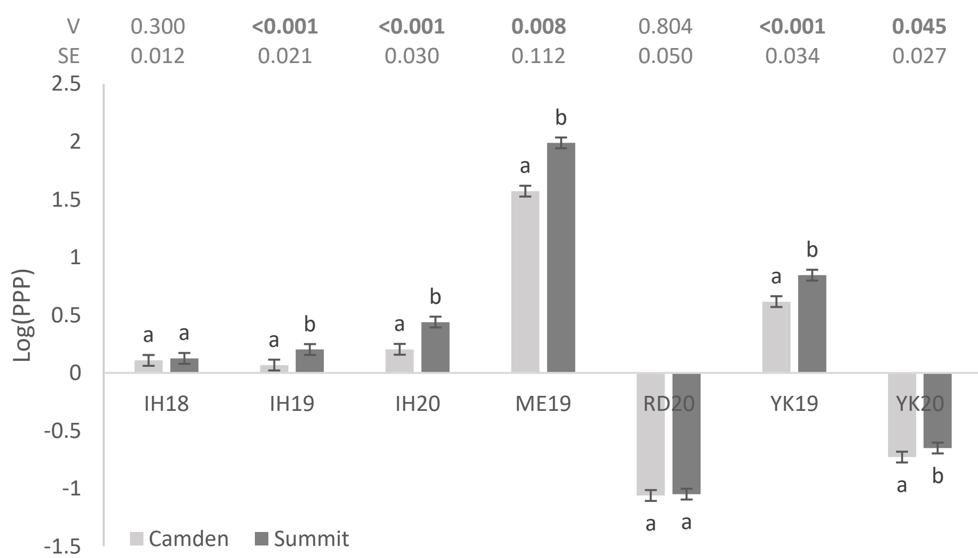

Figure 4. The effect of variety (V) on the number of panicles per plant at each site-year individually. Negative values are a result of the log transformation. F-test results for individual site-years (shown at top) are considered significant at P≤0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Lodging

There was no lodging observed at Indian Head in 2019, Melfort in 2018, 2019, and 2020, or Revers in 2020, leaving 6 site-years of data. Lodging was square-root transformed.

Averaged across site-years, the degree of lodging differed significantly between varieties, seeding rates, and there was a significant interaction between variety and seeding rate (Table 5). Lodging was higher with Summit than Camden overall, and the interaction showed that lodging was not affected by seeding rate with Camden, but was significantly higher at the 450 seeds/m^2 seeding rate than at the 300 seeds/m^2 rate with Summit (Figure 5). There was a significant site-year interaction with fungicide, and the variety by seeding rate interaction also varied with site-year (Table 6). When site-years were analyzed individually, the interaction with fungicide was such that only one of the six site-years (Yorkton 2020) had a significant fungicide effect, where untreated had significantly higher lodging than the flag-leaf timing, but neither differed significantly from the heading application (not shown). In contrast, there was a varied response to variety and seeding rate between site-years (Figure 6). At two of the site-years (Yorkton 2018 and 2020), only variety had a significant effect, with Summit showing significantly higher lodging than Camden. At Indian Head 2020, only seeding rate had a significant effect, with the higher seeding rate showing significantly more lodging. Indian Head 2018 had both a significant variety and seeding rate effect, consistent with the other site-years where Summit and the higher seeding rate both showed significantly more lodging. Two of the site-years (Redvers 2018 and Yorkton 2019) had significant variety by seeding rate interactions which were consistent with the average response across site-years. The results are as expected, since Camden has a very good rating for lodging, while Summit is rated as good. A higher seeding rate, and subsequently higher plant population, would be expected to have greater lodging, and fungicide was not expected to have a significant effect on lodging.

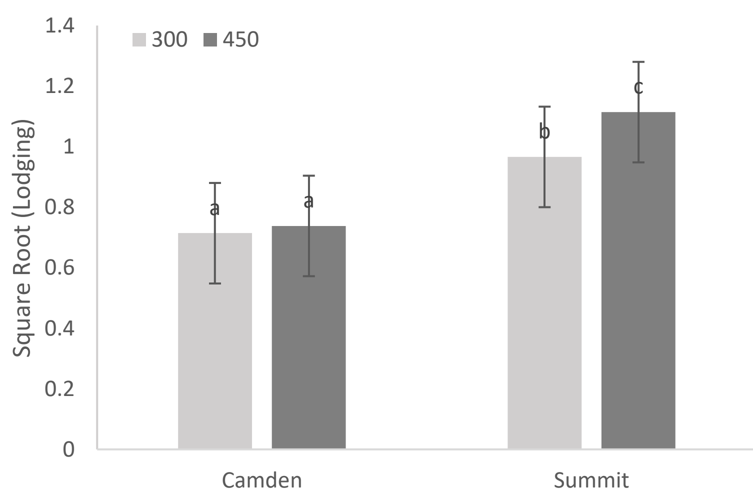

Figure 5. The interacting effect of variety and seeding rate on lodging across all site-years. Error bars indicate the standard error. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

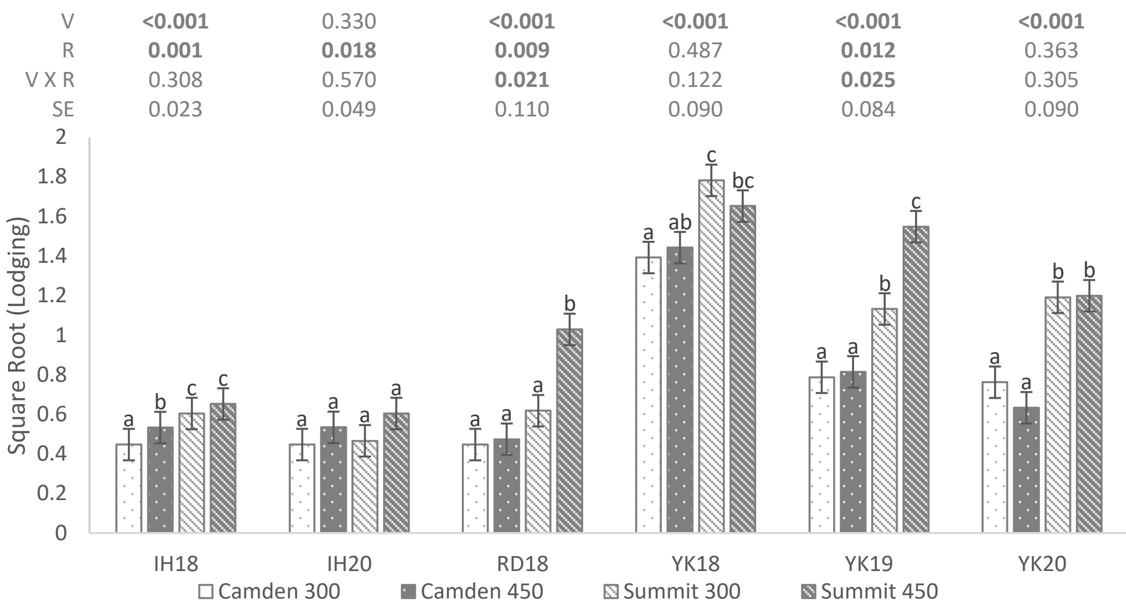

Figure 6. The effect of variety (V), seeding rate (R), and their interaction (V X R) on lodging at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P<0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Maturity

Maturity was recorded at all eleven site-years. Averaged across site-years, maturity differed significantly between varieties and fungicide treatments, but there were no significant interactions (Table 5). Despite the statistical significance, treatment effects on maturity were small when averaged across site-years. Maturity was significantly delayed with Summit compared to Camden, and the fungicide effect was such that flag leaf timing had significantly later maturity than heading, but neither differed significantly from untreated (Table 8). There was a significant site-year interaction with fungicide, and a three-way interaction with variety and seeding rate (Table 6). When site-years were analyzed individually, the interaction with fungicide was such that there was no significant effect of fungicide at nine site-years (not shown), and the effect differed between the other two site-years (Figure 7). At Melfort 2019, fungicide application at either timing resulted in significantly later maturity than untreated, while at Yorkton 2018, maturity was significantly delayed when fungicide was applied at flag leaf compared to heading timing, but neither differed significantly from untreated. Further, there was a varied response to variety and seeding rate when analyzed individually by site-year (Figure 8). At two site-years, Melfort 2019 and Redvers 2020, there was no effect of either variety or seeding rate on maturity. At two site-years, Melfort and Yorkton 2020, there was only a significant effect of variety, where Summit had significantly later maturity than Camden. At five of the site-years, both variety and seeding rate had significant effects on maturity, but the effects of either were not consistent across site-years. The variety by seeding rate interaction was significant at two site-years, indicating that the seeding rate effect varied between varieties, though again the response was not consistent. It was expected that Camden would have later maturity than Summit, based on their maturity ratings. A higher seeding rate would be expected to result in earlier maturity. Yet, regardless of the effect of seeding rate at each site-year, higher plant densities and fewer tillers or panicles per plant did not correspond to earlier maturity. Meanwhile, fungicide application would be expected to delay maturity, particularly if disease was present; however the effect of fungicide on maturity was not significant at a large majority of site-years. The results suggest that the effects of variety, seeding rate and fungicide on maturity are all highly dependent on environmental conditions.

Table 8. The effect of variety and fungicide treatment on maturity across all site-years. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

Effect	Treatment	
Variety	Camden	1.90 a
	Summit	2.11 b
	SE	0.06
Fungicide	Untreated	1.98 ab
	Flag Leaf	2.11 b
	Heading	1.93 a
	SE	0.06

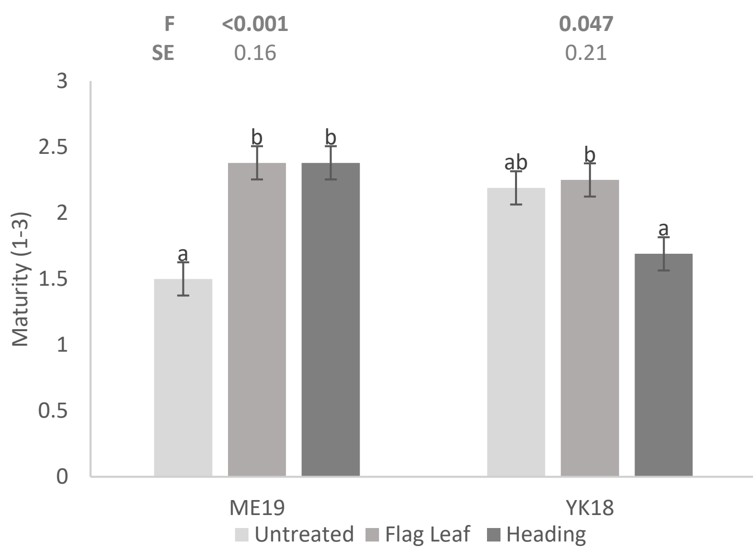

Figure 7. The effect of fungicide (F) on maturity at individual site-years. Nine site-years with non-significant fungicide effects are not shown. F-test results for individual site-years (shown at top) are considered significant at P≤0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

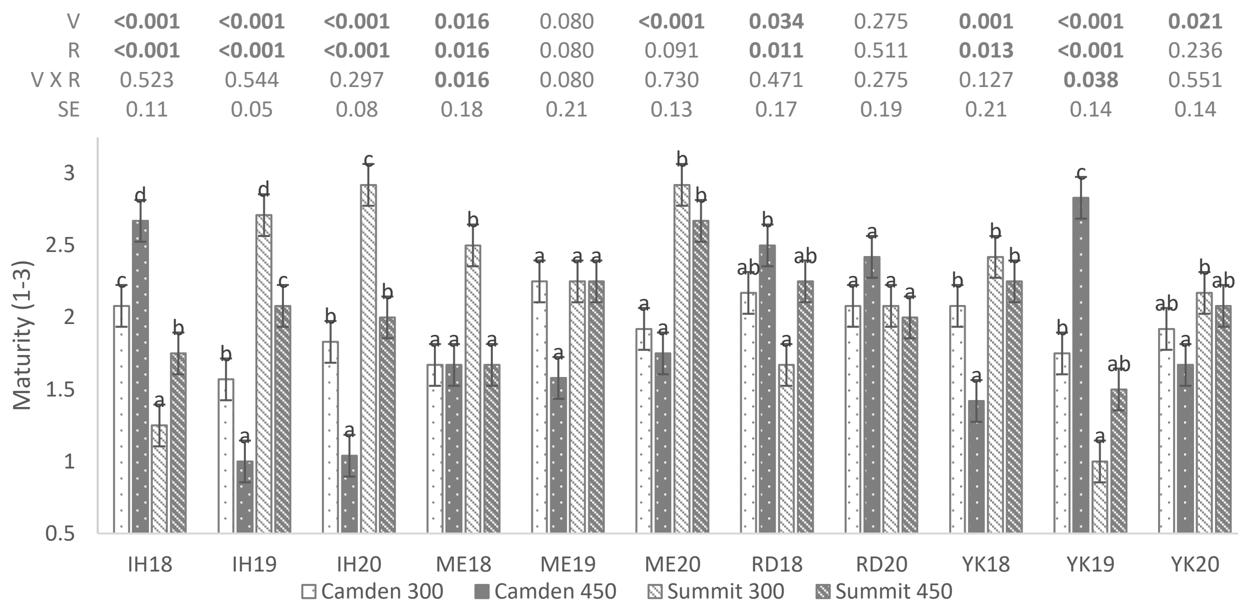

Figure 8. The effect of variety (V), seeding rate (R), and their interaction (V X R) on maturity at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P<0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Grain yield

Yield was recorded in all eleven site-years. Averaged across site-years, yield differed significantly between seeding rates and fungicide treatments, but there were no significant interactions (Table 5). Yield was significantly higher at the 300 seeds/m^2 seeding rate than the 450 seeds/m^2 seeding rate, contrary to what would be expected. The fungicide effect was such that flag leaf timing had significantly higher yield than heading, but neither differed significantly from untreated (Table 9). There was a significant site-year interaction with variety and fungicide (Table 6). When site-years were analyzed individually, the interaction with variety was such that the effect was not significant in five site-years, and the effect was not consistent across the remaining site-years (Figure 9). Camden would be expected to yield higher than Summit, based on varietal evaluations, thus this again indicates that the varietal response is dependent on environmental conditions. The interaction with fungicide was such that the effect was not significant at eight site-years, and the effect of fungicide timings was not consistent across the remaining three site-years (Figure 10). The flag leaf application timing yielded significantly higher than the heading application at all three site-years but did not always differ from the untreated.

Table 9. The effect of seeding rate and fungicide treatment on yield across all site-years. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

Effect	Treatment	
Seeding Rate	300	5358 b
	450	5248 a
	SE	412
Fungicide	Untreated	5320 ab
	Flag Leaf	5378 b
	Heading	5211 a
	SE	413

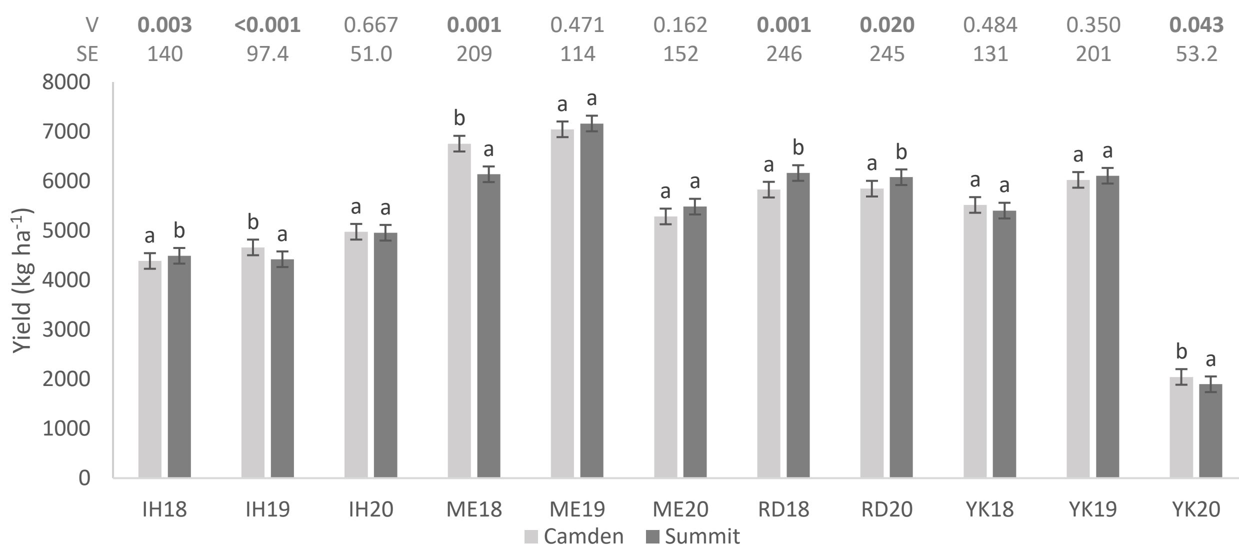

Figure 9. The effect of variety (V) on yield at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P≤0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

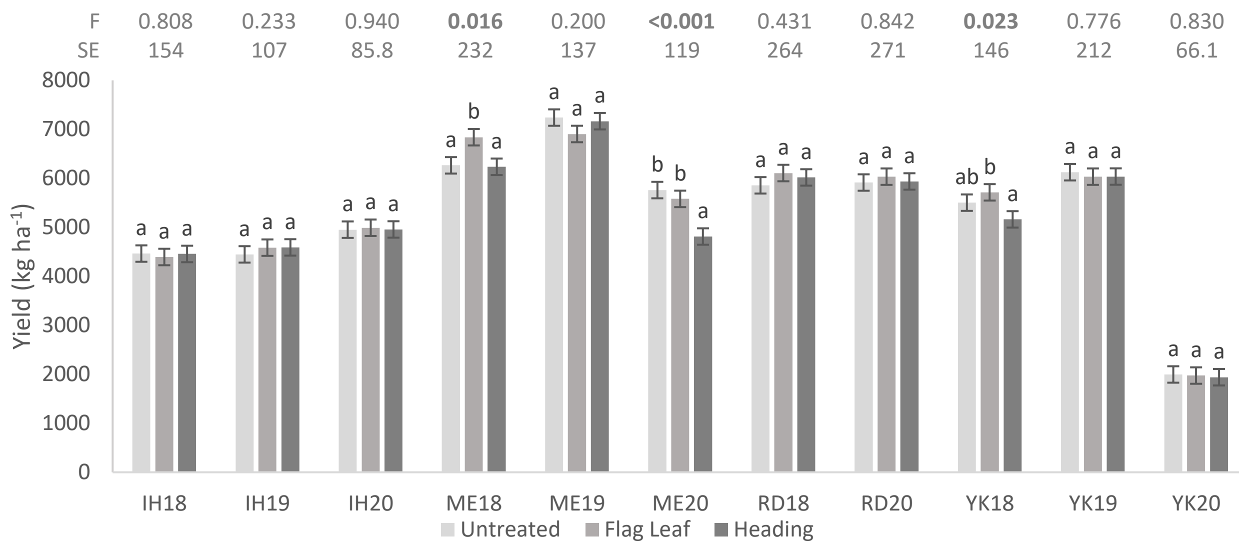

Figure 10. The effect of fungicide (F) on yield at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P≤0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Thousand kernel weight

Thousand kernel weight (TKW) was recorded in all eleven site-years. Averaged across site-years, TKW differed significantly between varieties only (Table 5). TKW was significantly higher with Camden (38.0 g 1000 seeds^{-1} ± 0.90) than with Summit (36.5 g 1000 seeds^{-1} ± 0.90). There was a significant site-year interaction with variety and seeding rate (Table 6). When site-years were analyzed individually, the interaction with variety was such that the effect was not significant at two site-years (Indian Head 2018 and Yorkton 2018), but was consistently higher with Camden than Summit at the remaining site-years, consistent with the overall response (not shown). The interaction with seeding rate was such that the effect was not significant at eight site-years, and the seeding rate effect was not consistent across the remaining three site-years (Figure 11).

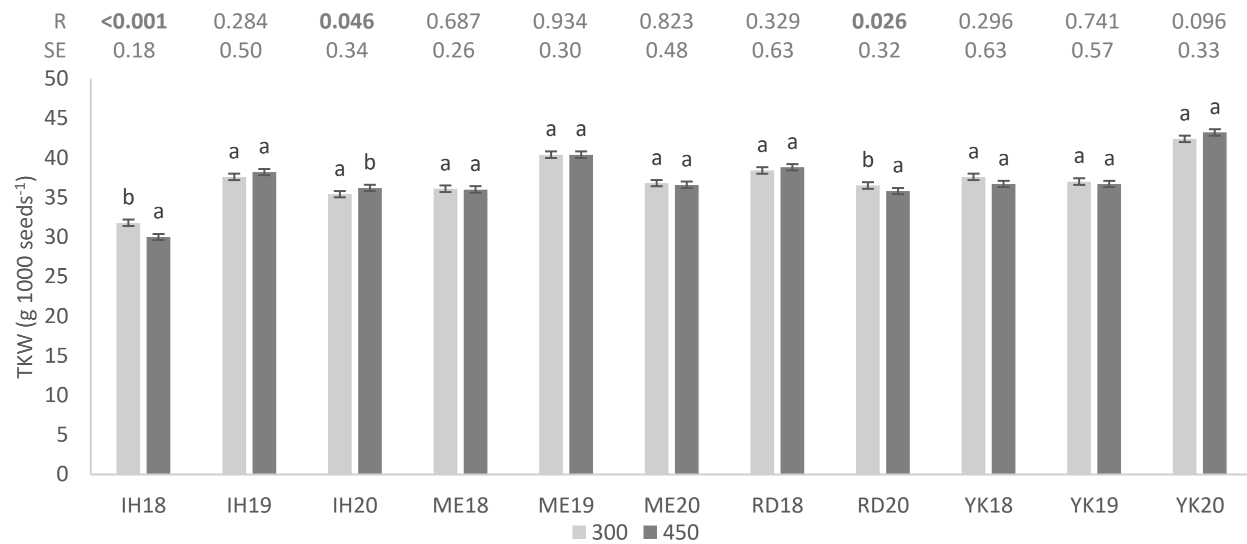

Figure 11. The effect of seeding rate (R) on thousand kernel weight (TKW) at each site-year individually. F-test results for individual site-years (shown at top) are considered significant at P≤0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

Disease severity

Crown and Stem rust were not found at any site-year with the exception of Yorkton 2020, at very minimal levels (3 plots only). The presence of rust in the Canadian Prairies is dependent on weather conditions blowing spores northward from the United States. There was also no evidence of Fusarium Head Blight at any site-year. Fusarium Head Blight has had minimal impact in oats historically and conditions generally were not favourable for development of the disease over the 3 years of this study. Thus, we were unable to assess the effects of integrated management on crown rust, stem rust, and FHB.

Leaf spot disease severity was analyzed as a repeated measure, comparing the baseline assessment at T1 (prior to flag-leaf application timing) to T2 (prior to fungicide application at heading) and T3 (milk stage) assessments. Time (T1, T2, or T3) was included as an additional fixed effect, with all two-, three-, and four-way interactions with the other treatment variables, for both the multi-site (site-year random, Table 10), and site-year interaction models (Table 11). Stepwise deletion of non-significant terms was used to simplify the models because of the large number of fixed effects and interactions. Non-significant interactions and fixed effects could be removed from the model as long as their removal did not result in significantly lower model fit (full vs simplified model, $P(\chi^2)>0.05$). Penultimate leaf assessments were only completed at a minimal number of locations (four site-years for T1-T2, and four site-years for T1-T3, and only three of these had all three assessment times), and so the analysis was only completed for the flag leaf assessments.

Table 10. F-test results of mixed-effects model analyses of flag leaf disease severity index (DSI), with site-year included as a random effect, to assess the overall effect of each treatment and interactions of the treatments across site-years. Effects are considered statistically significant if P≤0.05.

	DSI (T1 – T2)	DSI (T1 – T3)
Variety (V)	**0.001**	0.571
Seeding Rate (R)	0.603	0.354
Fungicide (F)	0.394	0.974
Time (T)	**<0.001**	**<0.001**
V X R	0.969	0.732
V X F	0.770	0.969
R X F	0.933	0.942
V X T	**<0.001**	0.381
R X T	0.435	0.052
F X T	0.077	0.771

Table 11. F-test results of mixed-effects model analyses of flag leaf disease severity index (DSI), with site-year included as a fixed effect, to assess the presence of site-year interactions with each treatment and factorial combination of treatments. Effects are considered statistically significant if P≤0.05.

	DSI (T1 – T2)	DSI (T1 – T3)
Variety (V)	**<0.001**	0.115
Seeding Rate (R)	0.370	**0.010**
Fungicide (F)	0.063	0.854
Time (T)	**<0.001**	**<0.001**
Site-year (S)	**<0.001**	**<0.001**
V X R	0.909	0.486
V X F	0.585	0.981
R X F	0.707	0.937
V X T	**<0.001**	**0.015**
R X T	0.178	**<0.001**
F X T	**0.001**	0.135
V X S	**<0.001**	**0.043**
R X S	0.570	**0.034**
F X S	**<0.001**	0.762
T X S	**<0.001**	**<0.001**
V X R X F	0.808	0.765
V X R X T	0.922	0.209
V X F X T	0.348	0.852
R X F X T	0.577	0.700
V X R X S	0.055	0.814
V X F X S	0.271	0.970
R X F X S	0.706	0.215
V X T X S	**<0.001**	**<0.001**
R X T X S	0.134	**<0.001**
F X T X S	**<0.001**	**<0.001**
V X R X T X S	-	**0.007**

Leaf spot disease ratings were not completed at T2 in Melfort in 2018 or 2020, leaving 9 site-years for the T1-T2 assessment. For the combined multi-site analysis (site-year random), the four-way interaction and all three-way interactions were non-significant and were removed from the model (full vs simplified model, $P(\chi^2) = 0.998$). Averaged across site-years, there was a significant change in DSI from T1 to T2, and the extent of change in DSI from T1 to T2 differed significantly between the two varieties, as evidenced by the significant variety by time interaction (Table 10). The interaction was such that the increase in DSI from T1 to T2 was significantly greater with Camden than with Summit (Figure 12). It is uncertain whether the two varieties would be expected to differ as the resistance levels of oat varieties to leaf spot disease is not often reported. For the site-year interaction model, the five-way interaction and all four-way interactions were non-significant and were removed from the model (full vs simplified model, $P(\chi^2) = 0.385$). There were significant site-year interactions with variety, time, and fungicide (Table 11). The two significant two-way interactions with site-year (V X T and F X T) were assessed individually by site-year, and all other interactions were nested within these two. When site-years were analyzed individually, the variety by time interaction was such that only time was significant at three site-years, showing an increase in DSI from T1 to T2, and the interaction was significant at the other six site-years, indicating that the change in DSI from T1 to T2 differed between varieties (Figure 13). In the site-years with significant variety by time interactions, Camden usually showed a greater increase in DSI from T1 to T2, consistent with the overall response, except for Yorkton 2018 where Summit showed a greater increase in DSI from T1 to T2. The fungicide by time interaction was such that there was no significant effect of fungicide or time at two site-years, and DSI at the remaining site-years either only changed with time (4 site-years) or had a significant fungicide by time interaction (3 site-years), indicating that the change in DSI from T1 to T2 differed between fungicide treatments (Figure 14). From T1 to T2, we would expect the flag leaf timing application to have less leaf disease than the untreated or heading application timing which has not been completed at the time of T2 assessment. However, the effect of fungicide treatment on the change in DSI from T1 to T2 was not consistent across the three site-years with significant interactions.

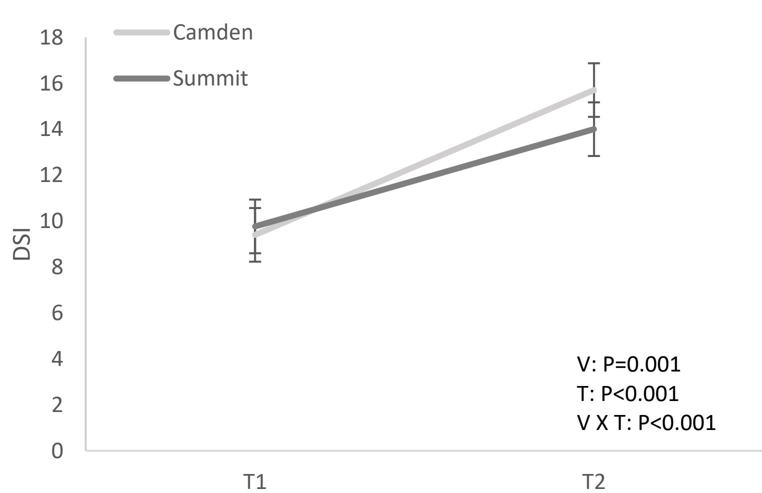

Figure 12. The effect of variety (V) and time (T) and their interaction (V X T) on flag leaf disease severity index (DSI) from T1 (prior to flag leaf fungicide application) to T2 (prior to heading application), across all site-years. Error bars indicate the standard error.

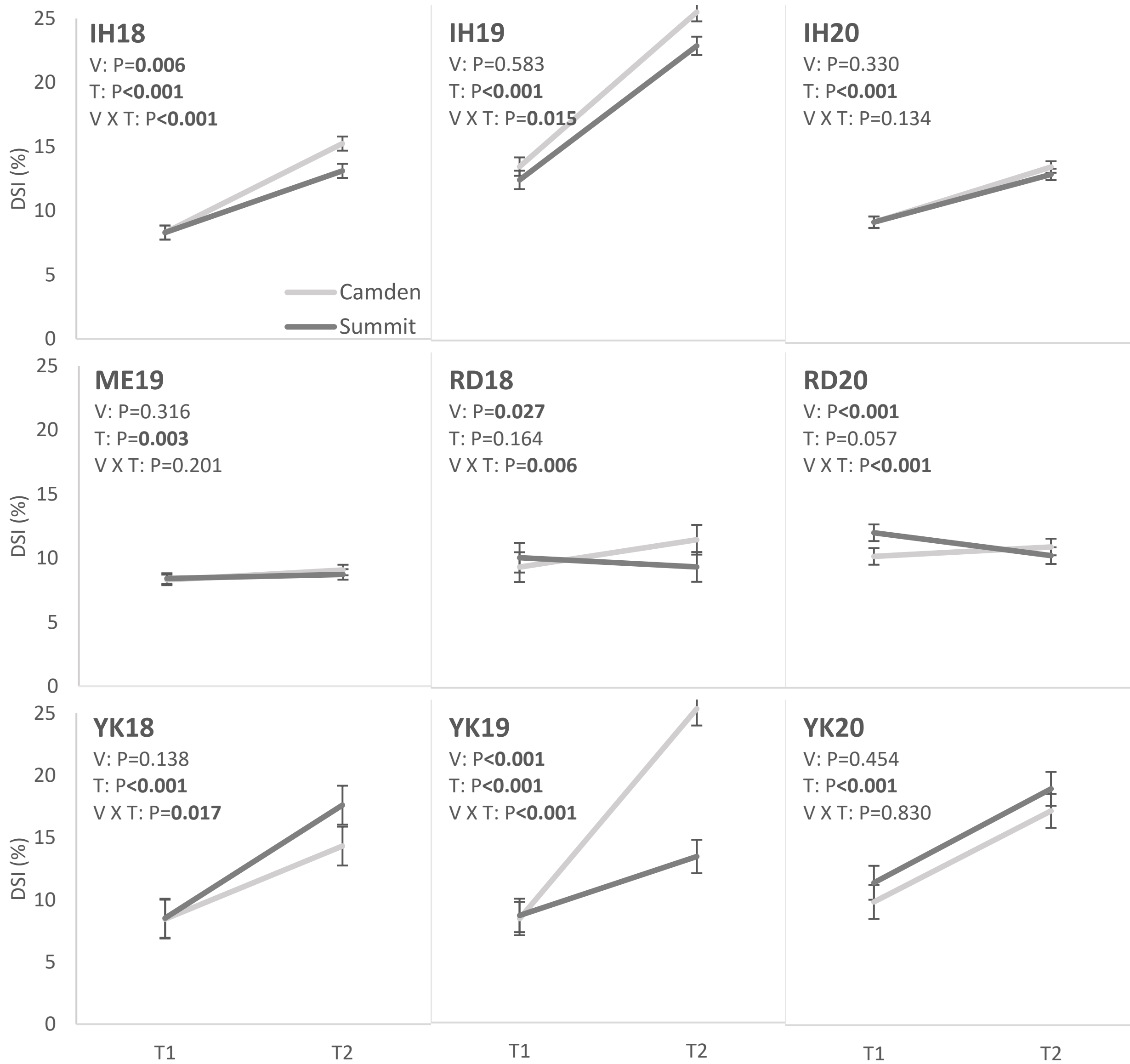

Figure 13. The effect of variety (V), time (T), and their interaction (V X T) on flag leaf disease severity index (DSI) from T1 (prior to flag leaf fungicide application) to T2 (prior to heading application) at each site-year individually. F-test results for individual site-years are considered significant at P≤0.05. Error bars indicate the standard errors of the individual mixed effects models.

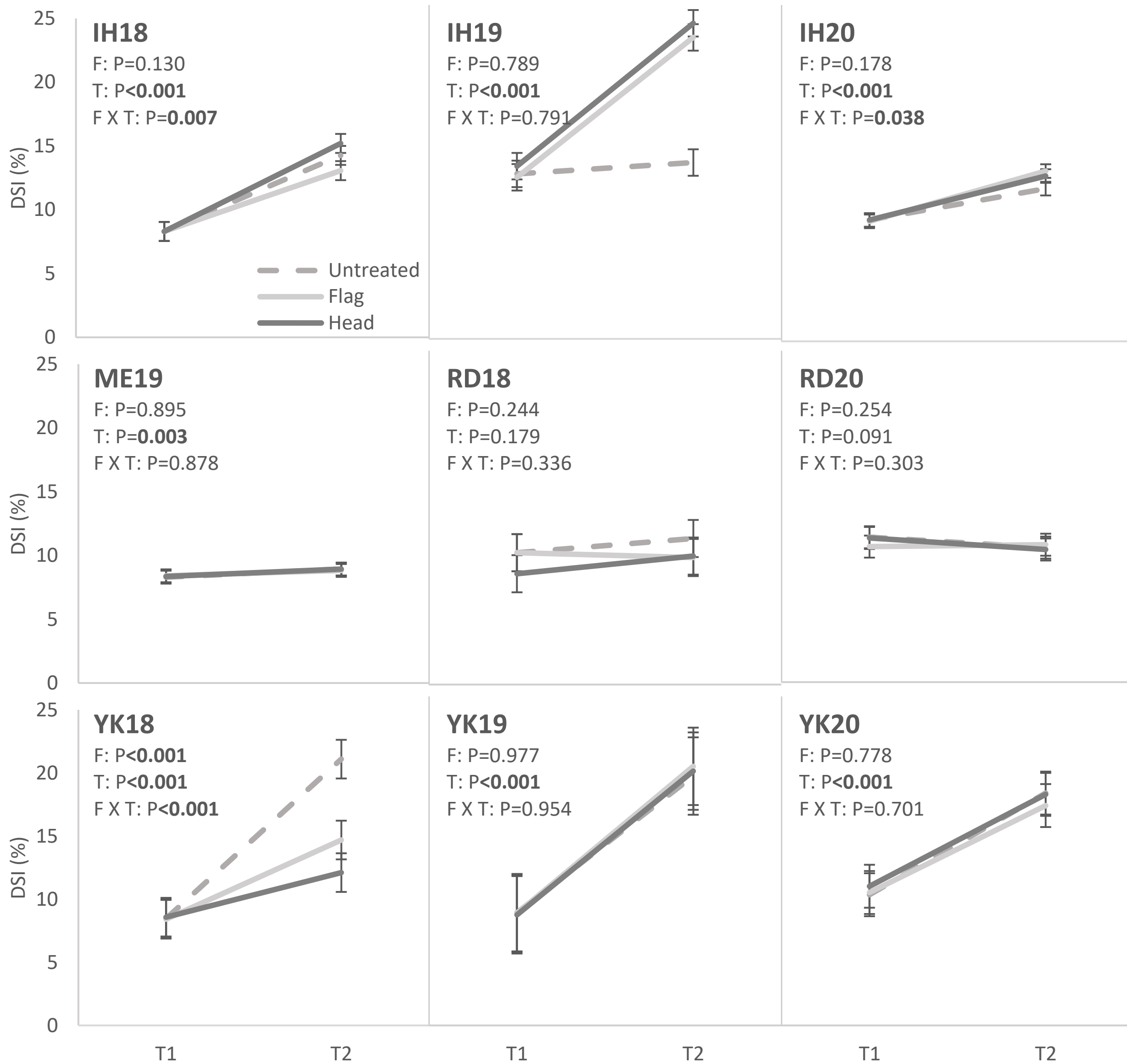

Figure 14. The effect of fungicide (F), time (T), and their interaction (F X T) on flag leaf disease severity index (DSI) from T1 (prior to flag leaf fungicide application) to T2 (prior to heading application) at each site-year individually. F-test results for individual site-years are considered significant at P≤0.05. Error bars indicate the standard errors of the individual mixed effects models.

Leaf spot disease ratings were not completed at T3 in Redvers or Yorkton in 2018, leaving 9 site-years for the T1-T3 assessment. For the combined multi-site analysis (site-year random), the four-way interaction and all three-way interactions were non-significant and were removed from the model (full vs simplified model, $P(\chi^2) = 0.999$). Averaged across site-years, there was a significant change in DSI from T1 to T3, but no other effects were significant (Table 10, not shown). For the site-year interaction model, the five-way interaction and all four-way interactions except one, site-year with variety by seeding rate by time, were non-significant and were removed from the model (full vs simplified model, $P(\chi^2) = 0.995$). There were significant site-year interactions with variety, seeding rate, fungicide, and time (Table 11). The only significant interaction with fungicide was the three-way interaction with time and site-year (F X T X S). This and the four-way interaction (V X R X T X S) were assessed individually by site-year, and all other interactions were nested within these two. When site-years were analyzed individually, the fungicide by time interaction was such that at six site-years, there was only a significant effect of time, while the fungicide by time interaction was significant at three site-years (Figure 15). However, the effect of fungicide treatment on the change in DSI from T1 to T3 was not consistent across the three site-years with significant interactions. The variety by seeding rate by time interaction was such that there were no significant effects at one site-year, only a significant increase with time at three site-years, and either a significant variety by time interaction or seeding rate by time interaction, indicating that the increase in DSI from T1 to T3 varied with either variety or seeding rate at these site-years, but not both (Figure 16). The variety effect and the seeding rate effect were not consistent across the site-years with significant interactions.

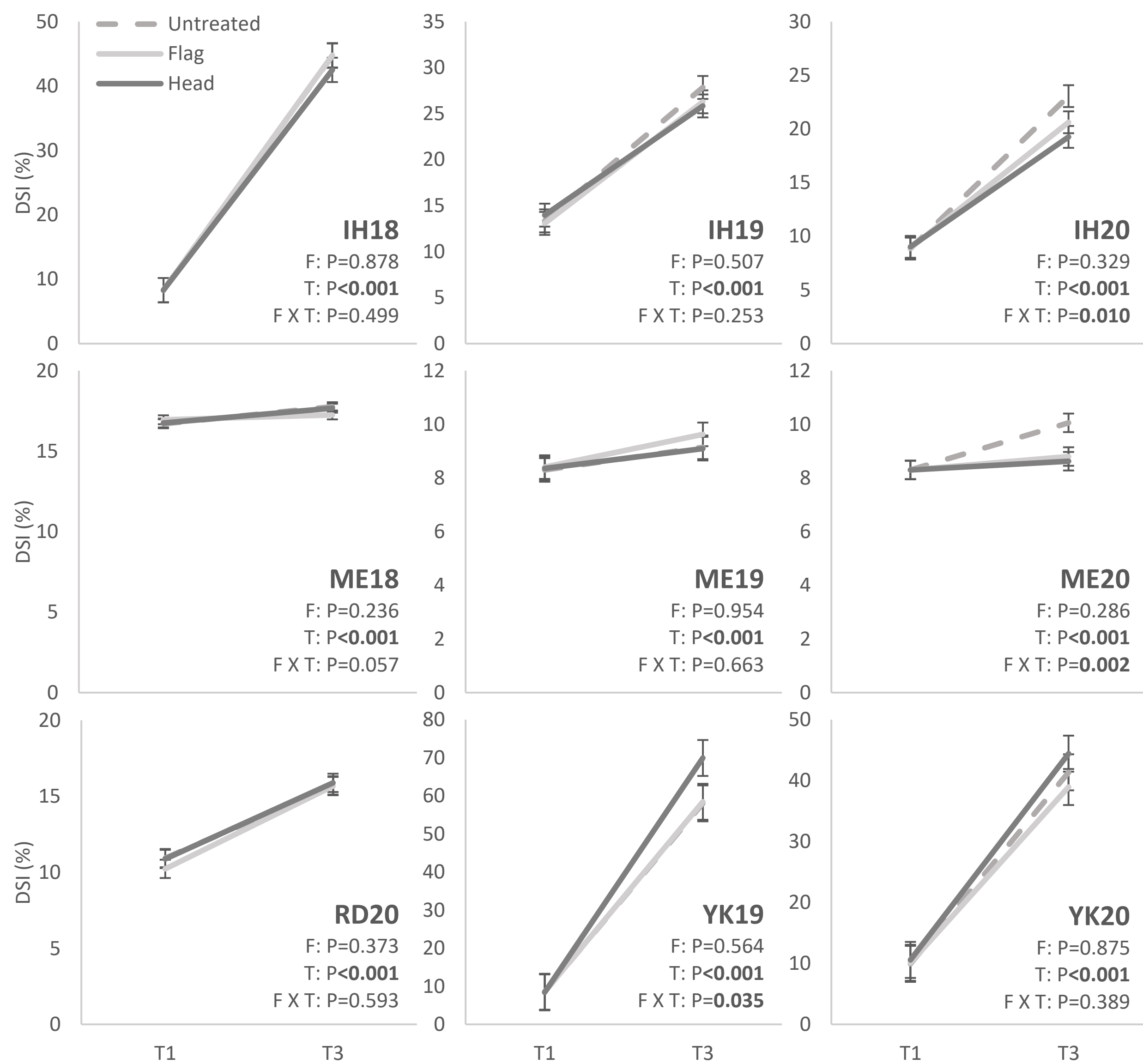

Figure 15. The effect of fungicide (F), time (T), and their interaction (F X T) on flag leaf disease severity index (DSI) from T1 (prior to flag leaf fungicide application) to T3 (milk stage) at each site-year individually. F-test results for individual site-years are considered significant at P≤0.05. Error bars indicate the standard errors of the individual mixed effects models.

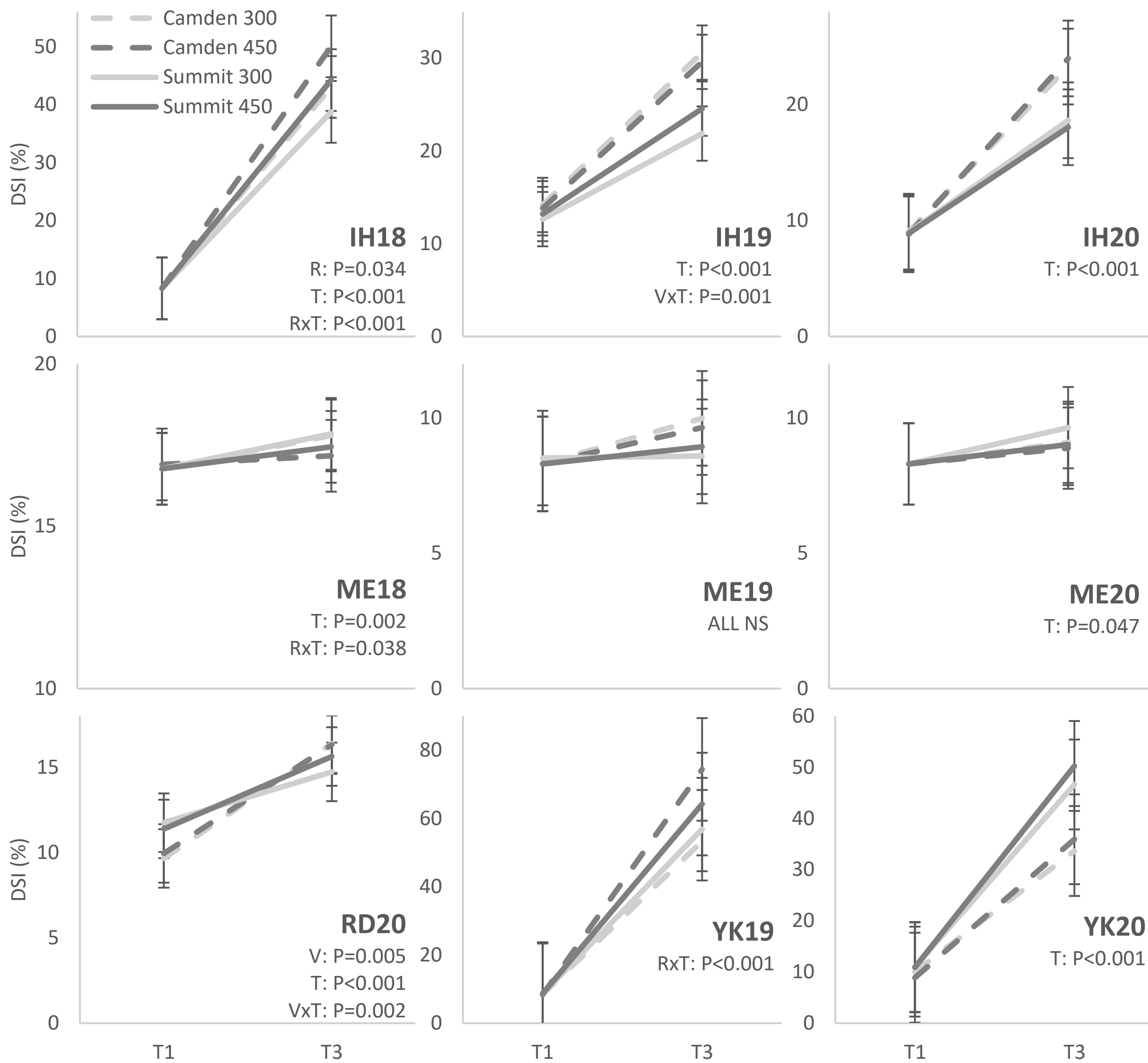

Figure 16. The effect of variety (V), seeding rate (R), time (T), and their interactions (V X T, R X T) on flag leaf disease severity index (DSI) from T1 (prior to flag leaf fungicide application) to T3 (milk stage) at each site-year individually. Only effects with significant F-test results are shown for each individual site-year. F-test results for individual site-years are considered significant at P≤0.05. Error bars indicate the standard errors of the individual mixed effects models.

Grain quality

Site-year interactions were not assessed for grain quality variables that were analyzed as composite samples (protein, plumps and thins, groat weight, and beta-glucans) because there was no replication of treatments within site-years. When averaged across site-years, variety, seeding rate, and fungicide treatments all had significant effects on several grain quality variables, and there were also significant interactions for two of the variables (Table 12).

Percent protein of the harvested grain was significantly affected by variety, seeding rate, and fungicide, and there were significant variety by seeding rate and variety by fungicide interactions (Table 12). The variety by seeding rate interaction was such that protein was significantly higher at the 450 seeds/m^2 seeding rate than at the 300 seeds/m^2 seeding rate with Summit, but there was no difference between seeding rates with Camden, and protein was significantly higher with Camden than Summit overall (Figure 17, left). The variety by fungicide interaction was such that protein was higher overall in Camden than Summit, but the effects of fungicide differed between the two (Figure 17, right). With Camden, percent protein was significantly higher with the heading application than with no fungicide application, but neither differed significantly from the flag leaf application. With Summit, percent protein was significantly lower with a flag leaf application than with either no fungicide or a heading application.

Percent plumps was rescaled by subtracting from 100 and then log-transformed. Large and small values are reversed because of the transformation used. Percent plumps was significantly affected by variety, seeding rate, and fungicide, but there were no interactions (Table 12). Percent plumps was significantly higher in Summit than Camden, at the 450 seeds/m^2 than at the 300 seeds/m^2 seeding rate, and with a fungicide application at heading compared to either a flag leaf application or no fungicide application (Table 13).

Percent thins was log transformed. Percent thins was significantly affected by variety, seeding rate, and fungicide but there were no interactions (Table 12). Percent thins was significantly higher in Summit than Camden, at the 300 seeds/m^2 seeding rate than at the 450 seeds/m^2 rate, and with no fungicide application compared to fungicide application at either timing (Table 13).

Percent groat weight was significantly affected by variety, seeding rate, and fungicide but there were no interactions (Table 12). Groat weight was significantly higher in Summit than Camden, at the 450 seeds/m^2 seeding rate than at the 300 seeds/m^2 rate, and with a heading fungicide application compared to a flag leaf application or no fungicide (Table 13).

Percent beta-glucans was significantly affected by variety, seeding rate, and there was a significant variety by fungicide interaction and the three-way interaction was also significant (Table 12). Beta-glucans were significantly higher in Camden than Summit overall, and at the 450 seeds/m^2 over the 300 seeds/m^2 overall (Figure 18). The interaction was such that there was a significant difference in beta-glucans between seeding rates only in Camden with no fungicide application.

Table 12. F-test results of mixed-effects model analyses of grain quality variables, with site-year included as a random effect, to assess the overall effect of each treatment and interactions of the treatments across site-years. Effects are considered statistically significant if P≤0.05.

	Protein	Plumps	Thins	Groat	Beta-glucan
Variety (V)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Seeding Rate (R)	**<0.001**	**0.031**	**<0.001**	**0.003**	**0.018**
Fungicide (F)	**0.001**	**<0.001**	**0.001**	**<0.001**	0.071
V X R	**<0.001**	0.450	0.284	0.661	0.906
V X F	**0.002**	0.149	0.956	0.577	**<0.001**
R X F	0.205	0.168	0.522	0.282	0.537
V X R X F	0.161	0.467	0.761	0.540	**<0.001**

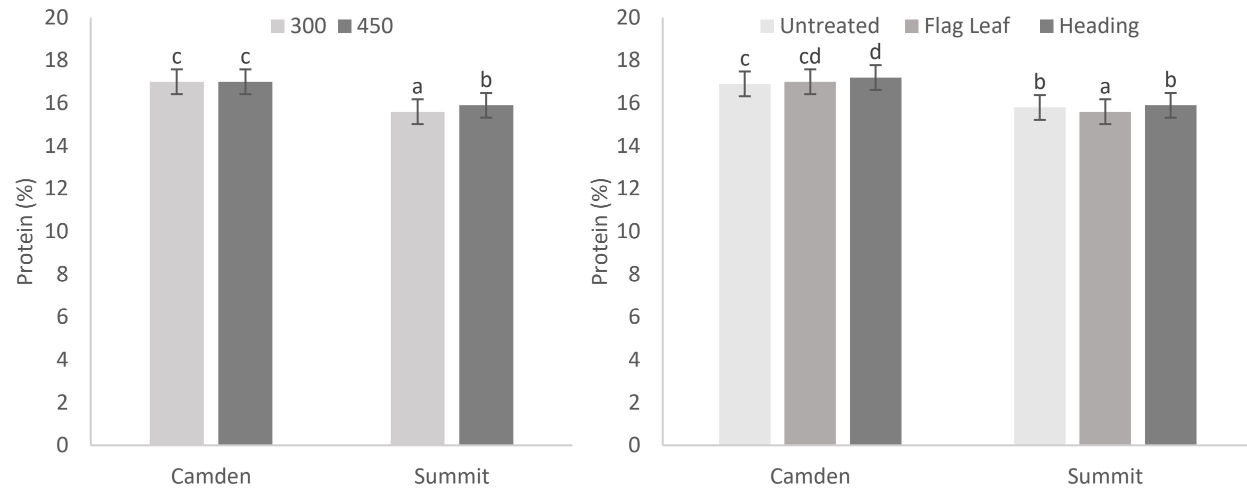

Figure 17. The interacting effect of variety and seeding rate (left) and variety and fungicide (right) on grain percent protein across all site-years. Error bars indicate the standard error. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

Table 13. The effect of variety, seeding rate, and fungicide treatment on plumps, thins, and groat weight across all site-years. Transformed values are shown; large and small values are reversed for plumps as a result of the transformation. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

Effect	Treatment	Log(100-Plumps)	Log(Thins)	Groat (%)
Variety	Camden	2.63 b	1.01 a	71.8 a
	Summit	2.57 a	1.12 b	76.3 b
	SE	0.16	0.17	0.94
Seeding Rate	300	2.62 b	1.11 b	73.9 a
	450	2.58 a	1.02 a	74.2 b
	SE	0.16	0.17	0.94
Fungicide	Untreated	2.64 b	1.12 b	73.9 a
	Flag Leaf	2.61 b	1.05 a	73.9 a
	Heading	2.55 a	1.03 a	74.4 b
	SE	0.16	0.17	0.94

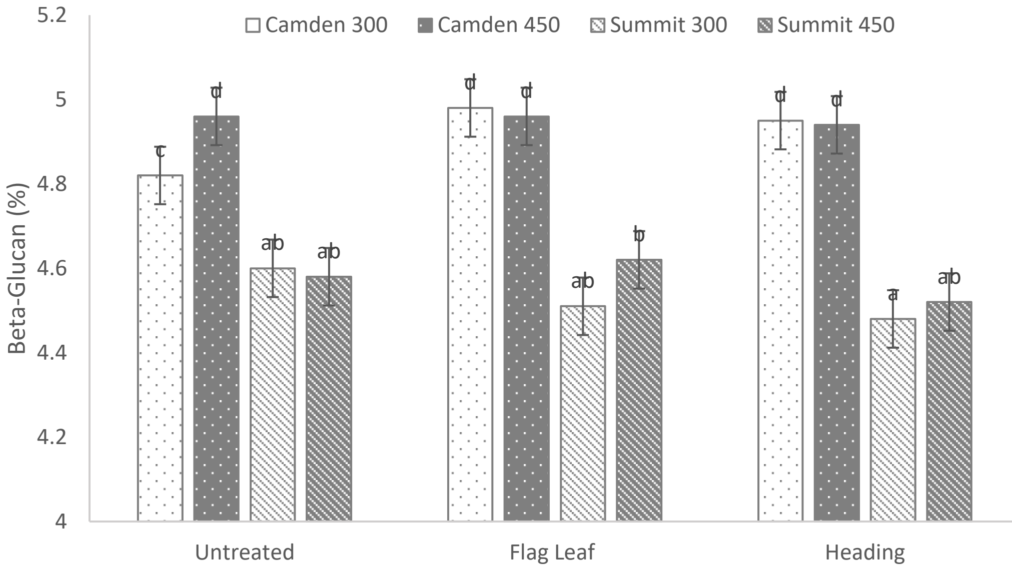

Figure 18. The interacting effects of variety, seeding rate, and fungicide on percent beta-glucans across all sites-years. Error bars indicate the standard error. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

Seed-borne diseases

Fusarium poae was square-root transformed. *F. poae* was not observed at meaningful levels in Yorkton in 2019, leaving 10 site-years. When averaged across site-years, only fungicide had a significant effect on the level of seed-borne *F. poae* (Table 14). The level of *F. poae* was significantly lower when fungicide was applied at heading (1.14 ± 0.39%) than when applied at flag leaf timing (1.33 ± 0.39%), but neither differed significantly from untreated (1.24 ± 0.39%) (transformed values). There was a significant site-year interaction with variety and rate (Table 15). When site-years were analyzed individually, there were no significant treatment effects at seven site-years, while there was only a significant effect of variety at one site-year, and the variety by seeding rate interaction was significant at two site-years (Figure 19). The effect of variety and the interaction were not consistent among the three site-years with significant effects.

Fusarium avenaceum was observed at meaningful levels at five site-years (Indian Head 2018 and 2020, Melfort 2020, Redvers 2020, and Yorkton 2020). When averaged across site-years, there was a significant seeding rate by fungicide interaction affecting the level of seed-borne *F. avenaceum* (Table 14). The level of *F. avenaceum* did not differ between fungicide treatments at the 300 seeds/m^2 seeding rate, but was significantly higher when fungicide was applied at flag leaf timing than at heading timing at the 450 seeds/m^2 seeding rate, but neither application timing differed significantly from untreated (Figure 20). There were no significant site-year interactions for *F. avenaceum* (Table 15).

Fusarium graminearum was observed at meaningful levels at five site-years (Indian Head 2019 and 2020, Melfort 2018, 2019, and 2020). When averaged across site-years, fungicide had a significant effect on the level of seed-borne *F. graminearum*, and there was again a significant seeding rate by fungicide interaction (Table 14). The interaction was such that the level of *F. graminearum* did not differ significantly between fungicide treatments at the 450 seeds/m^2 seeding rate, but was significantly higher in with no fungicide application than when fungicide was applied at heading timing at the 300 seeds/m^2 rate (Figure 21). There were no significant site-year interactions for *F. graminearum* (Table 15).

Fusarium sporotrichioides was observed at meaningful levels at five site-years (Indian Head 2019 and 2020, Melfort 2019 and 2020, Yorkton 2019). When averaged across site-years, only seeding rate had a significant effect on the level of seed-borne *F. sporotrichioides* (Table 14). The level of *F. sporotrichioides* was significantly higher with the 300 seeds/m^2 seeding rate (0.85 ± 0.32%) than with the 450 seeds/m^2 rate (0.62 ± 0.32%). There were no significant site-year interactions for *F. sporotrichioides* (Table 15).

Alternaria was observed at meaningful levels at all 11 site-years. There were no significant treatment effects or interactions when all site-years were combined (Table 14), however there were site-year interactions with both variety and fungicide (Table 15). The site-year interaction with variety was such that there was no significant difference between varieties at 9 of 11 site-years, while at two site-years (Indian Head 2018 and Yorkton 2018), the level of seed-borne *Alternaria* was higher with Camden than with Summit (not shown). The site-year interaction with fungicide was such that there were no differences between fungicide treatments at all but one site-year (Yorkton 2019), where untreated had significantly lower level of seed-borne *Alternaria* than the flag-leaf fungicide application, but neither differed significantly from the heading application (not shown).

Cochliobolus sativus was observed at meaningful levels at six site-years (Indian Head 2019, Melfort 2018 and 2019, Yorkton 2018, 2019, and 2020). When averaged across site-years, only variety had a significant effect on the level of seed-borne *C. sativus* (Table 14). The level of *C. sativus* was significantly higher with Summit (0.66 ± 0.21%) than with Camden (0.37 ± 0.21%). There was also a significant site-year interaction with variety (Table 15), which showed that the level of *C. sativus* was significantly higher with Summit at only three of the six site-years (Yorkton 2018, 2019, and 2020), while there was no significant difference between varieties at the other three site-years (not shown).

Table 14. F-test results of mixed-effects model analyses of seed-borne diseases, with site-year included as a random effect, to assess the overall effect of each treatment and interactions of the treatments across site-years. Effects are considered statistically significant if P≤0.05.

	F. poae	*F. avenaceum*	*F. graminearum*	*F. sporotrich.*	*Alternaria*	*C. Sativus*
Variety (V)	0.804	0.925	0.098	0.178	0.081	**<0.001**
Seeding Rate (R)	0.157	0.637	0.801	**0.033**	0.807	0.313
Fungicide (F)	**0.006**	0.066	**0.040**	0.133	0.087	0.108
V X R	0.268	0.396	0.451	0.526	0.260	0.238
V X F	0.632	0.494	0.458	0.163	0.772	0.247
R X F	0.471	**0.010**	**0.025**	0.322	0.609	0.525
V X R X F	0.416	0.829	0.906	0.989	0.702	0.330

Table 15. F-test results of mixed-effects model analyses of seed-borne diseases, with site-year included as a fixed effect, to assess the presence of site-year interactions with each treatment and factorial combination of treatments. Effects are considered statistically significant if P≤0.05.

	F. poae	*F. avenaceum*	*F. graminearum*	*F. sporotrich.*	*Alternaria*	*C. Sativus*
Variety (V)	0.802	0.924	0.097	0.178	0.077	**<0.001**
Seeding Rate (R)	0.154	0.634	0.800	**0.033**	0.804	0.276
Fungicide (F)	**0.008**	0.069	0.051	0.132	0.054	0.091
Site-year (S)	**<0.001**	0.094	**<0.001**	**<0.001**	**<0.001**	**<0.001**
V X R	0.265	0.392	0.449	0.525	0.254	0.202
V X F	0.628	0.488	0.455	0.162	0.767	0.197
R X F	0.466	**0.009**	**0.025**	0.320	0.601	0.471
V X S	0.155	0.316	0.899	0.253	**<0.001**	**<0.001**
R X S	0.456	0.636	0.209	0.234	0.966	0.818
F X S	0.646	0.463	0.842	0.124	**0.023**	0.541
V X R X F	0.411	0.826	0.905	0.989	0.696	0.275
V X R X S	**0.025**	0.827	0.889	0.646	0.734	0.873
V X F X S	0.770	0.152	0.463	0.760	0.910	0.662
R X F X S	0.469	0.703	0.086	0.210	0.646	0.508
V X R X F X S	0.766	0.139	0.478	0.951	0.391	0.245

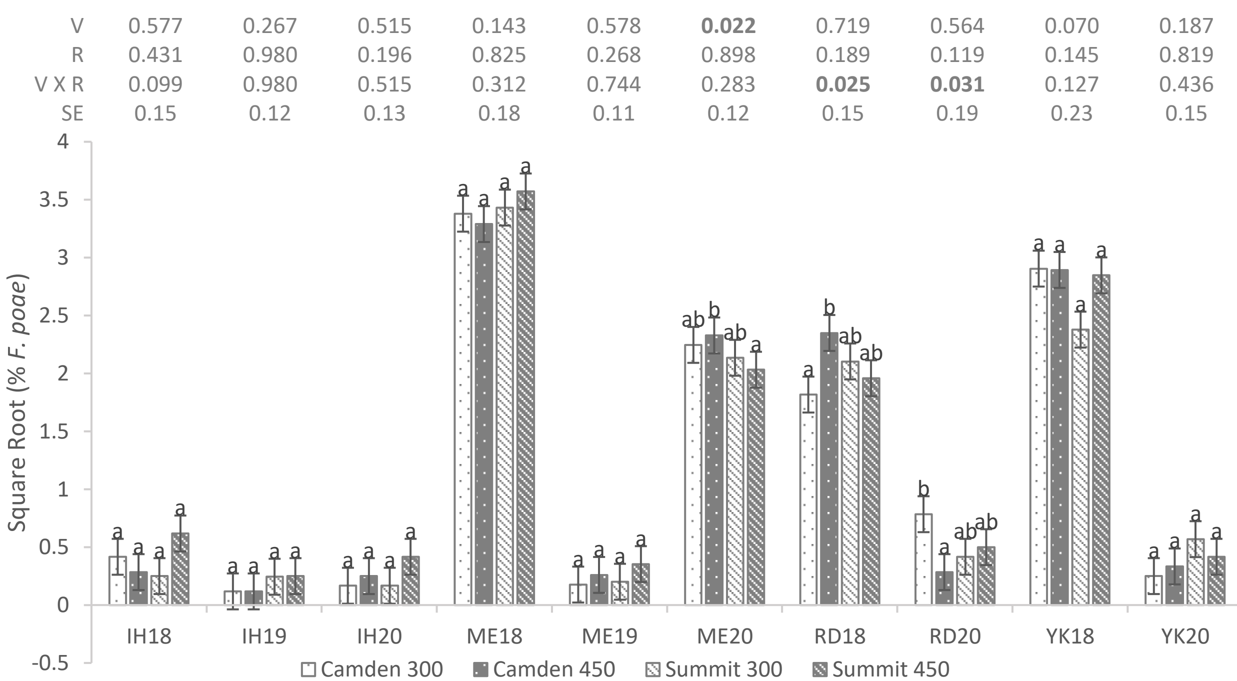

Figure 19. The effect of variety (V), seeding rate (R), and their interactions (V X R) on the level of seed-borne *Fusarium poae* at each site-year individually. F-test results for individual site-years (shown above) are considered significant at P≤0.05. Error bars indicate the standard error of the combined mixed effect model, while SE indicates the standard error of the individual mixed effects models. Letters indicate the separation of the estimated marginal means within individual site-years, using the Tukey method with alpha=0.05.

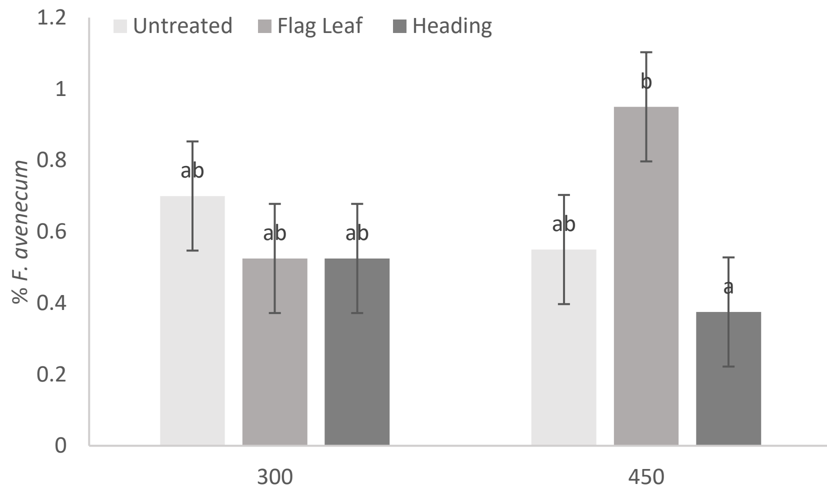

Figure 20. The interacting effect of seeding rate and fungicide on the level of seed-borne *Fusarium avenaceum* across all site-years. Error bars indicate the standard error. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

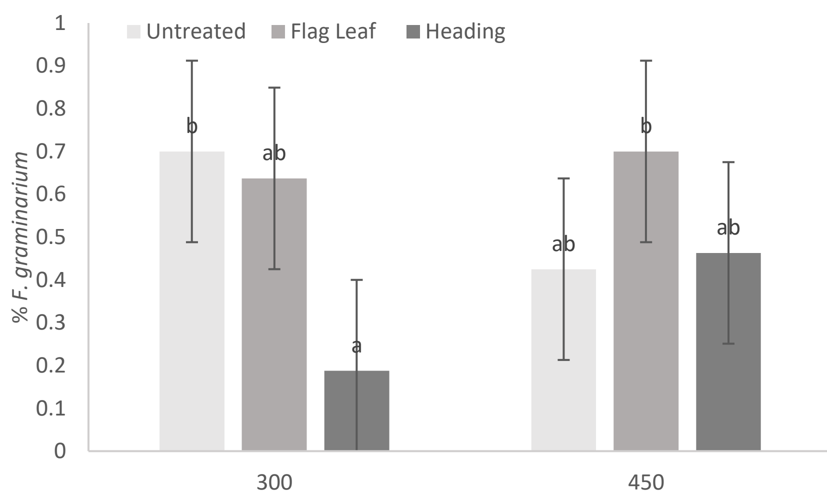

Figure 21. The interacting effect of seeding rate and fungicide on the level of seed-borne *Fusarium graminearum* across all site-years. Error bars indicate the standard error. Letters indicate the separation of the estimated marginal means using the Tukey method with alpha=0.05.

DISCUSSION

Objective 1: Understand the interaction between varietal resistance and fungicide application

The two varieties assessed in this study differed significantly for most of the variables measured, but there were rarely interactions with the fungicide treatments and, when there were fungicide effects, they were often not consistent or conclusive. Overall, plant density was similar between varieties, but Summit had a greater level of tillering and panicle development. Variety was secondary to seeding rate in its effect on tillering, but more equal to seeding rate in its effect on panicle development. Summit also had more lodging than Camden, and matured later overall, either of which may be related to the greater level of tillering and panicle development. However, lodging was not affected by fungicide, and the effect of fungicide on maturity was unrelated to varietal differences. The varieties did not differ in yield overall, and the effect of fungicide on yield was, again, unrelated to any varietal differences.

Camden had greater increase in leaf disease from T1 to T2 overall, but this did not lead to differential responses to fungicide application between the two varieties. Actually, leaf disease had only a weak response to fungicide application overall, with only three site-years showing a significant fungicide effect, and the effects of the fungicide treatments were not consistent across these three site-years. By the later leaf disease assessment at milk stage, the increase in leaf disease no longer differed between the two varieties overall, though the site-year interaction with variety showed that Camden had greater increase in leaf disease from T1 to T3 at two site-years. However, the fungicide treatments still did not differentially affect the two varieties' levels of leaf disease.

Seed quality is one area where there were slight differing responses to fungicide treatments between the two varieties. Overall, Camden had higher thousand kernel weight, and lower percent plumps, percent thins, and groat weight, but there was no interaction with fungicide treatment for any of these variables. Protein was higher in Camden than Summit overall, and their response to fungicide differed. Protein increased with later fungicide application in Camden, but neither of the fungicide timings differed significantly from no fungicide application in Summit. There was also a significant variety by fungicide interaction for beta-glucans, where beta-glucans were lowest with no fungicide application in Camden, but decreased with later fungicide applications in Summit.

In general, there were few differences between the two varieties in the level of seed-borne diseases. *Fusarium poae* was higher in Camden than Summit at one site year, *Alternaria* was higher in Camden than Summit at two site-years, and *Cochliobolus sativus* was higher with Summit than Camden overall, and at 3 site-years. The level of seed-borne disease was sometimes affected by fungicide treatments, but the fungicide effect did not differ between varieties.

In general, the varieties differed very little in their response to fungicide treatments, however, the effects of fungicide were also minimal and inconsistent, and disease levels were generally low across all site-years in this study.

Objective 2: Determine the impact plant populations have on optimal fungicide application

Seeding rate effects often differed between varieties but, similar to variety, rarely interacted with fungicide treatments. Across site-years, tillering and panicle development were consistently higher at the lower seeding rate, though overall there was no difference in tillering between seeding rates for Camden. The absolute number of tillers and panicles was still greater at the higher seeding rate (not reported). Lodging was often, but not always, higher at the 450 seeds/m^2 rate than the 300 seeds/m^2 rate. Overall, the effect of seeding rate on lodging was variety dependent; there was more lodging at the 450 seeds/m^2 rate than the 300 seeds/m^2 rate but only with Summit, which also had more lodging overall. Within sites and varieties, a higher rate of lodging overall corresponded to a greater difference between the two seeding rates. In other words, seeding rate effects were more likely to occur when environmental conditions were conducive to lodging and a variety susceptible to lodging was grown. Absolute numbers of panicles/m^2 were still greater at the higher seeding rate (not reported), despite the greater rate of tillering and panicle development at the lower seeding rate, which would explain the higher rate of lodging. Lodging was only affected by fungicide at one site-year, and the effect was independent of seeding rates. The effect of seeding rate on maturity was not consistent, and even actual plant densities, tiller densities, and panicle densities did not appear to correspond to differences in maturity. The effect of fungicide on maturity was also independent of seeding rate. Yield was higher at the lower seeding rate overall, but there was not a conclusive or consistent effect of fungicide. Fungicide effects were, again, unrelated to the effect of seeding rate on yield.

Seeding rate did not affect leaf disease from T1 to T2, and leaf disease from T1-T3 was affected by seeding rate at three site-years, but the effect was not consistent. The effect of fungicide on leaf disease was independent of seeding rates.

A higher seeding rate generally resulted in better seed quality, but again the effects were mainly independent of fungicide treatments. Seeding rate did not consistently affect the thousand kernel weight. The effect of seeding rate on protein was variety-dependent; protein was higher at the 450 seeds/m^2 rate with Summit but did not differ between seeding rates for Camden, which had higher protein overall. The effect of fungicide on protein was independent of seeding rate. Overall, percent plumps, groat weight, and beta-glucans were higher at the 450 seeds/m^2 rate, while percent thins were higher at the 300 seeds/m^2 rate. The only interaction of seeding rate with fungicide was a three-way interaction with variety on beta-glucans, where the difference in beta-glucans between seeding rates was only significant with no fungicide application in Camden.

There was an effect of seeding rate on the level of seed-borne *Fusarium poae* at two site-years only and the effect was not consistent and was independent of fungicide effects. The effect of fungicide on the level of seed-borne *Fusarium avenaceum* differed between seeding rates but the effect of fungicide in this interaction was inconclusive, as neither fungicide application timing differed from untreated. Similarly, the effect of fungicide on the level of seed-borne *Fusarium graminearum* differed between seeding rates, where there was significantly less disease with a heading application at the low seeding rate but no difference between fungicide treatments at the high seeding rate. The level of seed-borne *Fusarium sporotrichioides* was higher at the low seeding rate but was not affected by fungicide. The level of seed-borne *Alternaria* and *Cochliobolus sativus* were unaffected by seeding rate.

As with varietal effects, there were some significant differences between seeding rate treatments, but the effect of fungicide differed very little between seeding rates. However, this may again have been related to the minimal and inconsistent effects of fungicide application overall, attributable to the low disease levels across all site-years in this study.

Objective 3: Determine integrated disease management strategies in oats

Effects of variety, seeding rate, and fungicide were all very dependent on environments. Plant population, tillering, and panicle development were generally affected by variety and seeding rate, and these effects, in turn, may have contributed to varietal and seeding rate differences in lodging, leaf disease development, maturity, yield, and seed quality. There were often variety by seeding rate interactions, but seeding rate and variety effects were nearly always independent of fungicide treatments. Effects of fungicide application were inconsistent and often inconclusive, as untreated treatments performed as well as either of the fungicide application timings, even when there were significant differences between the treatments. Fungicide effects would likely have been more frequent and consistent if environmental conditions had been conducive to disease development.

Though there were significant effects of variety, neither variety consistently showed superior agronomic performance. Variety by seeding rate interactions were such that, with Summit, crop development was more sensitive to changes in seeding rate while Camden was more consistent across seeding rates. This may be because of known differences in crop physiological characteristics such as lodging and tillering, but also could be a result of unknown and unreported genetic differences, so it is difficult to extrapolate these findings to other varieties.

Conclusions & Recommendations

Producers should continue to combine several practices to manage disease in oats, as the effects can be additive, if not interactive. The differential response of varieties to changes in seeding rate should be confirmed for several more oat varieties. Further, as emergence, tiller, and panicle development are highly influenced by environmental conditions, the effects of actual plant population and tiller or panicle density on crop development and disease management should be examined. The effectiveness of applying fungicide for disease management does not appear to vary with varieties or seeding rates, and the decision to apply fungicide, and at what timing, should be based on environmental conditions being conducive to disease development. Leaf spot disease was most prevalent across site-years in this study, but fungicide applications at heading nonetheless appeared to have some effect on crop quality.

LITERATURE CITED

Bates, D., Maechler, M., Bolker, B., and Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67:1-48.

Bowen, K., Hagan, A., Pegues, M., and Jones, J. (2016). Yield Losses due to Crown Oat Rust in Winter Oats in Alabama. Plant Health Progress. 17:95-100.

Fetch, T., McCallum, B., Menzies, J., Rashid, K., and Tenuta, A. (2011). Rust diseases in Canada. Prairie Soils & Crops Journal. 4:86-96.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. Journal of Statistical Software 82:1-26.

Length, R. (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.4.

May, W.E., Ames, N., Irvine, R.B., Kutcher, H.R., Lafond, G.P., and Shirtliffe, S.J. (2014). Are fungicide applications to control crown rust of oat beneficial? Can. J. Plant Sci. 94: 911-922.

McCallum, B.D., Fetch, T., and Chong, J. (2007). Cereal rust control in Canada. Australian Journal of Agricultural Research. 58:639-647.

Picinini, E.C. and Fernandes, J.M. (1994). Efficacy of fungicide for controlling crown rust of oats. Fitopatologia Brasilerira. 19: 74-78.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Soovali, P. and Koopel, M. (2011). Timing of fungicide application for profitable disease management in oat (*Avena sativa* L.). Agriculture. 98 (2): 167-174.

Table A-1. Seeding, foliar fungicide application, and harvest dates at all four locations from 2018-2020.

Location	Seeded	Flag Leaf Fungicide	Heading Fungicide	Harvested
		2018		
Indian Head	May 7	June 25	July 3	Aug 10
Melfort	May 15	June 29	July 13	Sept 28
Redvers	May 7	June 25	July 7	Aug 21
Yorkton	May 11	June 21	July 15	Aug 30
		2019		
Indian Head	May 7	July 2	July 8	Aug 29
Melfort	May 17	July 5	July 29	Oct 7
Redvers	May 4	June 24	July 10	Aug 20
Yorkton	May 8	July 3	July 14	Sept 4
		2020		
Indian Head	May 8	June 30	July 9	Aug 19
Melfort	May 23	July 11	July 24	Aug 31
Redvers	May 5	June 19?	July 3?	
Yorkton	May 5	June 23	July 6	Aug 20

Table A-2. Herbicide, insecticide, and pre-harvest aid applications at four locations from 2018 to 2020.

	Pre-Seed Herbicide	In-crop Herbicide
Indian Head		
2018	Glyphosate 540 (0.67 L/ac)	Buctril M (0.41 L/ac)
2019	Glyphosate 540 (0.67 L/ac)	Prestige XC (0.17 L/ac A + 0.8 L/ac B)
2020	Roundup Transorb HC (0.67 L/ac)	Prestige XC (0.17 L/ac A + 0.8 L/ac B)
Melfort		
2018	Glyphosate 540 (0.5 L/ac)	Prestige XC (0.17 L/ac A + 0.8 L/ac B)
2019	Glyphosate 540 (0.5 L/ac) + Heat (21 mL/ac)	Prestige XC (0.17 L/ac A + 0.8 L/ac B)
2020	Glyphosate 540 (0.61L/ac) + Heat LQ (59 mL/ac)	Prestige XC (0.13L/ac A + 0.6L/ac B)
Redvers		
2018	NA	Buctril M (0.4 L/ac)
2019	NA	Buctril M (0.4 L/ac)
2020		
Yorkton		
2018	NA	NA
2019	NA	Frontline XL (0.5 L/ac)
2020	NA	Prestige

Table A-3. Modified Cobb Scale used for rating Stem and Oat Crown Rust severity.

Rating	% Infection
1	0.37
5	1.85
10	3.7
20	7.4
30	11.1
40	14.8
50	18.5
60	22.2
70	25.9
80	29.6
90	33.3
100	37.0

Table A-4. Horsfall-Barratt Scale used for rating leaf spot disease severity.

Rating	% Infection
1	0
2	0-3
3	3-6
4	6-12
5	12-25
6	25-50
7	50-75
8	75-87
9	97-94
10	94-97
11	97-100
12	100