

ARTICLE

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Response of oat grain yield and quality to nitrogen fertilizer and fungicides

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Abstract

Recently agronomists and producers have expressed interest in combining higher nitrogen (N) rates with a fungicide application even when disease intensity is low. The objective of this study was to evaluate the effect of fungicide application and N rates on grain yield and oat quality (*Avena sativa* L.). The experimental design was a split plot with fungicide (none, pyraclostrobin, propiconazole + trifloxystrobin) as the main plot, and eight N rates as sub-plots (5, 20, 40, 60, 80, 100, 120, and 140 kg ha⁻¹). This study was conducted in 2012 and 2013 at two locations in Saskatchewan, Melfort and Indian Head. Disease intensity was very low for crown rust (*Puccinia coronata*) and low-to-moderate for all other foliar diseases, and with no large effect on grain yield and quality. No interaction between fungicide and N was observed. A curvilinear increase in grain yield occurred as the N rate increased from 5 to 140 kg ha⁻¹. Increasing the N rate caused a small linear decrease in test weight. At a low oat price, \$130 t⁻¹, the N rate that maximized economic return was sensitive to N fertilizer price. As the crop price increased the optimum N rate was 100 kg ha⁻¹. In conclusion, our results indicate that using an N rate of 100 kg ha⁻¹ provided the most consistent economic returns when the crop price is between \$162 and \$194 t⁻¹. There is no beneficial interaction between fungicide and N for growers using higher N rates at low disease intensity and resistant genotypes.

1 | INTRODUCTION

In recent years oat (*Avena sativa* L.) production has transitioned from a late seeded fill crop to an economically viable crop, offering premium markets and opportunities for producers. In 2016, Canadian oat production surpassed three million tonnes with Saskatchewan expected to account for approximately 55% of Canada's oat production nationally (Statistics Canada, 2017a). The oat milling industry has shifted from the Midwestern United States to Western Canada throughout the past two decades, and oats have transformed from a domestic crop to a major Canadian

export. In 2017, oat exports are expected to account for 66% of oat use in Canada (Statistics Canada, 2017b). This high export demand is due to the high nutritive value of oat, being labeled as a heart healthy food ingredient and an increased demand for use in human food products (US Food and Drug Administration, 2018; Welch, 2011). These export markets require a high quality grain, triggering growers to push for higher yielding and better quality oat production. Recent research in oat has led to improved production practices providing growers with incentives to increase production.

Currently, growers targeting high yields and high returns have started to apply in excess of 90 kg ha⁻¹ of nitrogen (N)

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fertilizer to their oat crop; however, studies have not consistently supported this level of N fertilizer use. Previous studies observed optimal N responsiveness in oat in a range from 30 to 120 kg N ha⁻¹ fertilizer (Brinkman & Rho, 1984; Lafond, May, & Holzapfel, 2013; May, Mohr, Lafond, Johnston, & Craig Stevenson, 2004; Pecio & Bichoniski, 2010). A study investigating the response of oat to N observed severe lodging after the N rate surpassed 84 kg N ha⁻¹ followed by grain yield decreasing beyond this rate (Brinkman & Rho, 1984). At two of the four site-years the optimum N fertilizer rate was 28 and 54 kg N ha⁻¹. Lafond et al. (2013) found in one out of three site-years there were small grain yield increases when the N rate was increased to 120 kg ha⁻¹ while in the other two site-years 60 kg N ha⁻¹ was sufficient to maximize grain yield. In addition, the loss in grain quality especially test weight can be quite significant as the N rate increases decreasing the value of the harvested crop (Lafond et al., 2013; May et al., 2004). More recently, Holzapfel (2014) observed decreased test weights and increased lodging as N rates increased, validating previous findings. Holzapfel's results could not support N rates surpassing 61 kg ha⁻¹, since adequate grain yield benefits were not seen past these rates.

Diseases management in oat is important in maintaining high yields. Among the diseases, crown rust [*Puccinia coronata* Corda var. *avenae* f.sp. *avenae* (Urban & Marková)] is the most economically important. Yield losses due to the crown rust between 14 and 35% have been widely reported (Bissonnette, D'Arcy, & Pedersen, 1994; Clark, 1968; May et al., 2014). Leaf blotch diseases [*Pyrenophora avenae* Ito & Kuribayashi and *Stagonospora avenae* (Weber) Eriks] are responsible for another 5–10% of yield losses, seed weight and quality reduction (Bailey, Gossen, Gugel, & Morrall, 2003). Breeding for genetic resistance and the use of fungicides are the primary means of controlling disease. When the genetic resistance is overcome or not incorporated into an oat cultivar a fungicide application can protect grain yield and quality. Fungicide applications have been used in various environments around the world to reduce grain yield loss from crown rust (Dietz, Schierenbeck, & Simón, 2019; Federizzi, Pacheco, & Nava, 2015; van Niekerk, Pretorius, & Boshoff, 2001). On the northern portion of the North American Great Plain, May et al. (2014) found that the benefit of a fungicide application increased as the susceptibility to crown rust of the cultivar grown increased, along with increased disease pressure; however, when disease pressure was low, very little benefit in grain yield or quality was derived from a fungicide application. In addition, early seeding improved grain quality and further reduced any benefit from a fungicide application when disease pressure was low, making a fungicide application unnecessary in moderately resistant cultivars when combined with early seeding. However, field scale trials conducted at Indian Head, Saskatchewan found that a fungicide application increased grain yield in 50% of the trials with the yield increase ranging from 0–19% (Holzapfel,

Core Ideas

- Are nitrogen (N) and fungicides synergistic in oat development, grain yield, and grain quality?
- In the absence of moderate disease development, N and fungicide did not interact for the measured variables.
- At a lower crop price the economic return was sensitive to the price of N fertilizer.
- As the crop price increased the optimum N rate was 100 kg ha⁻¹.

2014). A study in Wisconsin found that a fungicide increased grain yield even in cultivars with a range of disease resistance (Mourtzinis, Conley, & Gaska, 2015). In addition, BASF has been promoting the application of pyraclostrobin to produce greener leaves, stronger stems, and reduced stress resulting in higher yield crops (BASF, 2009).

In a review paper Bartlett et al. (2002) listed a variety of physiological processes directly affected by strobilurins including carbon dioxide compensation point, leaf senescence, ACC synthase and thereby ethylene biosynthesis, chlorophyll content, photosynthetic activity, stomatal aperture, water consumption, plant antioxidant enzyme activity, endogenous levels of abscisic acid and other plant hormones, and nitrate reductase activity. However, the impact of strobilurins that differ from other fungicides is unclear. Wu and von Tiedemann (2001) and Zhang, Zhang, Chen, Zhou, and Wang (2010) found that several fungicide families including triazoles, strobilurins and phenamacril (cyanoacrylate compound) all delayed senescence in wheat due to enhanced antioxidant enzyme activity protecting the plants from harmful active oxygen species (AOS). It appears that the physiological processes behind the changes in plant development stimulated by the application of a strobilurin has not been fully elucidated.

It has been suggested that to maximize the unique benefits of improved yield, crop quality, and harvestability, pyraclostrobin should be applied preventatively, before the onset of disease symptoms (BASF, 2009). This creates a strong encouragement for growers to apply a fungicide prophylactically regardless of the crown rust resistance of the oat cultivar or the level of disease severity. This greening effect did not result in improved economic returns in winter wheat (Weisz, Cowger, Ambrose, & Gardner, 2011) or soybean (Mahoney, Vyn, & Gillard, 2015; Swoboda & Pedersen, 2009). The marketing and promotion of fungicide use at low disease levels increases the need for more research on the benefits of fungicides in oats when disease pressure is low.

To date, few studies have investigated the interaction between N and fungicide as elements of crop management. In Estonia, Sooväli, Kangor, and Tamm (2010) found a small

to moderate increase in disease intensity of crown rust and leaf disease as the N rate was increased and a fungicide application prevented the increase in disease severity as the N rate increased but these differences did not transfer into an effect on grain yield. Pecio and Bichoniski (2010) studied the interaction of N and fungicide and found no interaction between N and fungicide. Dietz et al. (2019) also investigated N fertilizers combined with fungicide protection programs but similarly observed no interaction between fungicide and N for grain yield. There is a dearth of research concerning the interaction between N and fungicide, and whether fungicide application can offset increased lodging and decreased test weights seen in oat crops when N rates are increased.

Some producers are using higher N rates, some are applying fungicides prophylactically and some are utilizing both agronomic practices. The two objectives of this study were to evaluate the effect of fungicide application and N rate on the grain yield and quality of oat in Saskatchewan and to provide growers with information on the benefits of N application combined with fungicide treatment as a management practice in oat crops.

2 | MATERIALS AND METHODS

This study was conducted in 2012 and 2013 at two locations in Saskatchewan, Melfort (52°49' N, 104°36' W, elevation 490 m) and Indian Head (50°33' N, 103°39' W, elevation 579 m). The soil type at Indian Head is Indian Head Heavy Clay, a Rego Black Chernozem (Udic Boroll) and at Melfort the soil is a Melfort Silty Clay loam, Orthic Black Chernozem (Mitchell, Mess, Clayton, & Edmunds, 1994). The experimental design was a split plot with four replicates with three fungicide treatments (none, pyraclostrobin (Methyl 2-(((1-(4-chlorophenyl)-1H-pyrazol-3-yl)oxy)methyl)phenyl)(methoxy)carbamate, Headline) or propiconazole (1-[[2-(2,4-dichlorophenyl)4-propyl-1,3-dioxolan-2-yl]methyl]-1H-1,2,4 triazole) + trifloxystrobin (methyl 2-methoxyimino-2-[2-[[1-[3-(trifluoromethyl)phenyl]ethylideneamino]oxymethyl]phenyl]acetate, Stratego) as the main plot and eight applied N fertilizer rates as the sub-plot (5, 20, 40, 60, 80, 100, 120, and 140 kg ha⁻¹). Labeled rates of each fungicide treatment were applied with 25 g a.i. ha⁻¹ of both propiconazole (125 g L⁻¹) + trifloxystrobin (125 g L⁻¹) in one treatment and 40 g a.i. ha⁻¹ of pyraclostrobin (250 g L⁻¹) in the other treatment. A spray volume of 111 L ha⁻¹ was used. The fungicides were applied at Zadoks 45 after the flag leaf was fully emerged (Zadoks, Chang, & Konzak, 1974). All fertilizer was side banded during seeding and placed approximately 2.5 cm to the side, and 5 cm below the seed. Phosphorous in the form of monoammonium phosphate (MAP) (11-52-0-0) was applied at a rate of 23 kg P₂O₅ ha⁻¹ in each plot. Fertilizer N was applied as urea (46-0-0-0), and MAP, with the amount of urea adjusted to account for the

N in the MAP. The amount of urea applied was adjusted to achieve the desired N rate for each treatment. Plot sizes were 10.7 m by 4 m at Indian Head and 10 m by 4 m at Melfort. The spacing between seed rows was 30.5 cm at Indian Head and 20.3 cm at Melfort. Research was performed using a no-till cropping system and was seeded into canola (*Brassica napus* L.) stubble. The oat cultivar Triactor was used and the target plant density was 300 plants m⁻². Triactor is a high yielding cultivar and currently has good resistance to crown rust and moderate resistance to leaf disease and poor resistance to stem rust (Anonymous, 2017). The trials were seeded on 14 May at Indian Head and 17 May at Melfort in 2012, and on 15 May at Indian Head and on 22 May at Melfort in 2013. Glyphosate (540 g a.e. L⁻¹) was applied at 383 g a.e. ha⁻¹ before tests were seeded to control emerged weeds. In-crop broadleaf herbicides were determined for each site and seeding date according to weed species density.

2.1 | Data collection

Soil was sampled at two depths: 0–15 cm and 15–60 cm; N was determined at both depths, and P was determined at 0–15 cm. A NaHCO₃ extraction procedure (Hamm, Radford, & Halstead, 1970) was used to estimate residual soil N (NO₃⁻), and phosphorus (PO₄⁻³-P). Oat population densities were determined in each plot in two 1 m sections of crop row, 3-to-5 wk after seeding and similarly, oat panicles were quantified after panicle emergence. Ten flag leaves and ten penultimate leaves were assessed on fungicide non-sprayed control plots when fungicide was sprayed (Zadoks 47), and in all plots at crop late milk stage (Zadoks 77) for crown rust and stem rust using a modified Cobb Scale (Peterson, Campbell, & Hannah, 1948). Leaf spot diseases were assessed at the same time on the same leaves as the crown rust using the Horsfall-Barratt scale (0–11) for leaf spot diseases (Horsfall & Barratt, 1945). These ratings were then converted to percentage of leaf area affected by the disease. Leaf spot diseases on oat in Saskatchewan are usually caused by *Pyrenophora* leaf blotch and *Stagonospora* leaf blotch. Plant height (cm) was measured at two places in each plot. Lodging was rated in each plot at physiological maturity using a 1 to 10 scale (1 = standing, 10 = completely lodged). Grain yield was determined with a self-propelled plot combine with a harvest area per plot of 42 m² at Indian Head and 13 m² at Melfort. Each sample was cleaned using a dockage tester as specified by the Canadian Grain Commission (2012) Official Grain Grading Guide. Grain yield was expressed on a clean grain basis with 13% kernel moisture. Kernel weight (grams per 1000 seed kernels), was calculated by weighing 1000 kernels. Kernels per panicle was calculated using panicles per square meter, grain yield, and kernel weight. Kernels per square meter was calculated using grain yield and kernel weight. Plump seed was recorded as the portion of the grain sample mass that

TABLE 1 Summary of weather conditions at sites located near Indian Head and Melfort, SK, in 2012 and 2013

Location/year	Daily average temperature						Precipitation					
	April	May	June	July	Aug.	Sept.	April	May	June	July	Aug.	Sept.
	°C						mm					
Indian Head												
2012	4.1 ^a	9.9	16.5	19.2	17.1	12.6	45.4	79.4	51	124.6	30.4	0
2013	-4.6	11.9	15.3	16.3	17.1	14.3	5.8	17.1	103.8	50.4	6.1	14.8
30 yr. long term average	4.2	10.8	15.8	18.2	17.4	11.5	22.6	51.7	77.4	63.8	51.2	35.3
Melfort												
2012	2.6	9.6	15.2	18.9	17.1	12.4	30.7	57.5	115.6	100.2	68.9	14
2013	-3.9	12.0	15.4	16.4	17.7	14.4	5.8	19	97.9	103.2	11.7	18.1
30 yr. long term average	2.8	10.7	15.9	17.5	16.8	10.8	26.7	42.9	54.3	76.7	52.4	38.7

^aEnvironment and Climate Change Canada, 2018.

fell through a 2.18 mm by 19.05 mm screen (5.5/64 in by 3/4 in slotted sieve). Test weight was measured as specified by the Canadian Grain Commission (2012) Official Grain Grading Guide to determine milling quality. To measure the percentage of the kernel that consisted of the groat, the kernel hulls were removed using a compressed air, oat laboratory-dehulling machine (oat huller LH 5095, Codema, USA). A 50-g sample was used with a dehulling time of 60 s, an air pressure of 690 kPa, and a blast gate aperture of 1.5–2.0 cm (Doehlert & McMullen, 2001; Doehlert, McMullen, & Baumann, 1999). Groat percentage was recorded as the mass of groat divided by the mass of the whole oat multiplied by 100.

2.2 | Economics of nitrogen fertilizer rate

To increase the understanding of the impact of N rate on the financial return to producers a simple economic analysis was conducted. The change in gross return (\$ ha⁻¹) as the N rate increase was calculated at three oat prices, 130, 162, and 194 \$ t⁻¹ and three cost of N fertilizer, 1, 1.5, and 2 \$ kg⁻¹. The gross return at each N rate was calculated for each of the nine oat price by N price combinations. The change in gross return was calculated within each replicate giving a change in gross return for each plot. The 5 kg N ha⁻¹ rate was used as the base return for each oat price by N price combination. The difference in return at each N rate compared to the base N rate was calculated from grain yield (kg ha⁻¹), crop price (\$ kg⁻¹), N rate (kg ha⁻¹) and N price (\$ kg⁻¹) at each of the nine oat price by N price combinations.

$$\text{Gross return} = \text{grain yield} \times \text{crop price} - (\text{N rate} \times \text{N price})$$

2.3 | Statistical analysis

Mixed model analysis of data was conducted using the Proc MIXED model procedure in SAS software (Littel, Milliken, Stroup, & Wolfinger, 2006). The effect of replicate was considered random, and the effects of the year, location (site),

N rate, and fungicide fixed. With sites considered fixed, inferences regarding optimal N and fungicide applications for a single oat cultivar cannot be extended to all possible sites in the Eastern Canadian Prairies. Statistical significance was declared at $P < .05$ for all analysis.

3 | RESULTS AND DISCUSSION

3.1 | Climatic and soil conditions

Monthly average temperature and accumulated precipitations from 1 April to 30 September are provided in Table 1 (Environment and Climate Change Canada, 2018). At Indian Head, the 2012 growing season experienced sufficient precipitation early in the growing season, followed by hot and dry conditions throughout the summer months. The 2013 season saw cool temperatures in early spring resulting in later seeding dates. The remainder of the growing season saw climatic conditions representative of the typical range of conditions seen in the Eastern Prairies. At Melfort during 2012 precipitation was above normal for April through August, with more than double normal precipitation during June; however, September was drier than normal. Mean monthly temperatures were within one degree of normal for all months except July and September 2012, which were above normal. During 2013 the soil was saturated with moisture due to excess precipitation the preceding year along with ample snowmelt; however, dry conditions during April and May allowed seeding to proceed, but somewhat later than normal for the region. Precipitation was above normal in June and July, but below normal during August and September. Temperatures during May and September were more than one degree above normal, and more than one degree cooler than normal during July 2013. Overall moisture was rarely limiting during either year at Melfort.

The residual level in the soil the fall prior to seeding at Indian Head was 11 kg N (NO₃⁻) ha⁻¹ and 10 kg P (PO₄⁻³)

in 2012, and 33 kg N ha⁻¹ and 10 kg P in 2013. At Melfort the residual levels were 36 kg N ha⁻¹ and 54 kg P in 2012, and 32 kg N ha⁻¹ and 20 kg P in 2013. The potassium level in the soils was 540 kg K ha⁻¹ or greater at each of the sites.

3.2 | Plant and panicle density

Plant density was only affected by site (Table 2). This indicates that the separation of fertilizer and seed through side banding was managed sufficiently to prevent the increasing rate of N from damaging the emerging seedling. Each of the four site-years differed in plant density with numbers being highest at Indian Head in 2012 (270 plants m⁻²) intermediate at Melfort in both 2012 (208 plants m⁻²) and 2013 (217 plants m⁻²), and lowest at Indian head in 2013 (165 plants m⁻²) (LSD = 8). Plant density ranged from 211 to 220 plants m⁻² across the eight N rates with no clear trend.

Panicle density was affected by site, N rate and site × N rate (Table 2). All sites followed the same linear trend for panicle density to increase as N rate increased (Table 3). A similar response was observed by other studies (Brinkman & Rho, 1984; May et al., 2004; Mohr et al., 2007). As expected fungicide did not affect panicle density (Table 2). The no fungicide treatment had an average of 362 panicles m⁻² while the oat treated with pyraclostrobin had 352 panicles m⁻² and 356 panicles m⁻² when treated with propiconazole + trifloxystrobin. Panicle density was highest at Indian Head, 2012 and Melfort, 2013 at 385 and 383 panicles m⁻² respectively, lower at Indian Head in 2013 (335 panicles m⁻²), and lowest at Melfort in 2012 (323 panicles m⁻²) (LSD = 11).

3.3 | Height and lodging

Height was affected by site, N rate, and site × N rate (Tables 2 and 3). Heights differed among sites with the greatest differences observed between Melfort, 2013 and Indian Head, 2012. It appeared that temperatures during June and July when crop stems were elongating had an inverse relationship with crop height. In 2012, at Indian Head the temperatures during these 2 mo were relatively hot, but relatively cool at Melfort in 2013. All sites saw increases in height as the N rate increased with a curvilinear increase at all sites except Melfort in 2013 where the increase was linear (Table 3). Several studies observed an increase in height as the N rate increased (Brinkman & Rho, 1984; May et al., 2004; Mohr et al., 2007). Height averaged across N rates and sites was 111 cm when pyraclostrobin was applied, 112 cm when propiconazole + trifloxystrobin were applied and 113 cm when no fungicide was applied.

Lodging was affected by site, N rate, and site × N rate, but was not affected by fungicide (Table 2). Only two site-years

of data were collected (Indian Head, 2012 and Melfort, 2012). At Indian Head, 2012 there was a large spike in lodging when N rates surpassed 100 kg ha⁻¹. Interestingly this site had the shortest plant height of the four sites. While, at Melfort, 2012 saw very little changes in lodging as N increased following no trend and consistently remained low (Figure 1). Studies by Brinkman and Rho (1984) and Browne, White, and Burke (2003) reported a large increase in lodging as the N rate increased at one site in 1 yr. In another study conducted in Manitoba, observed a more consistent increase in lodging as the N rate increased (Mohr et al., 2007). In this study, lodging was not affected by fungicide application. Lodging remained at an average of 2 for pyraclostrobin, propiconazole + trifloxystrobin, and no fungicide. While, other studies with a range of cultivars and a greater level of disease intensity, observed decreased lodging with the application of a fungicide (May et al., 2014; Mourtzinis et al., 2015).

3.4 | Crown rust and leaf spot diseases

In both years, crown rust was not observed at Melfort and at very low levels at Indian Head. The levels at Indian Head were too low for statistical analysis. Leaf spot disease was rated on both the flag leaf and the penultimate leaf (flag – 1). The leaf spot disease complex on both leaves was affected by N rate, fungicide, site, and site × fungicide (Table 2). Leaf spot disease on the flag leaf followed a linear trend, slightly increasing with higher N rates (Figure 2). Leaf spot disease remained below 4% when averaged across sites. At the same time, there was a curvilinear increase in leaf disease on the penultimate leaf. Once the N rate reached 80 kg ha⁻¹ changes in the leaf disease rating were very small. Sooväli et al. (2010) found a similar trend of a small increase in disease severity as the N rate increased. The increase in disease as the level of N fertilizer increased may be due to any of several factors. Increasing the N increases the amount of green leaf tissue available for infection, plus it can increase the density of the plant canopy increasing humidity and moisture. Also, increasing the N rate increases the length of time green leaf tissue is available for infection and with the increased growth and leaf size it might even slightly increase the leaves susceptibility to infection. Further study is required to better understand the mechanisms behind the increase in leaf disease as the N rate increased.

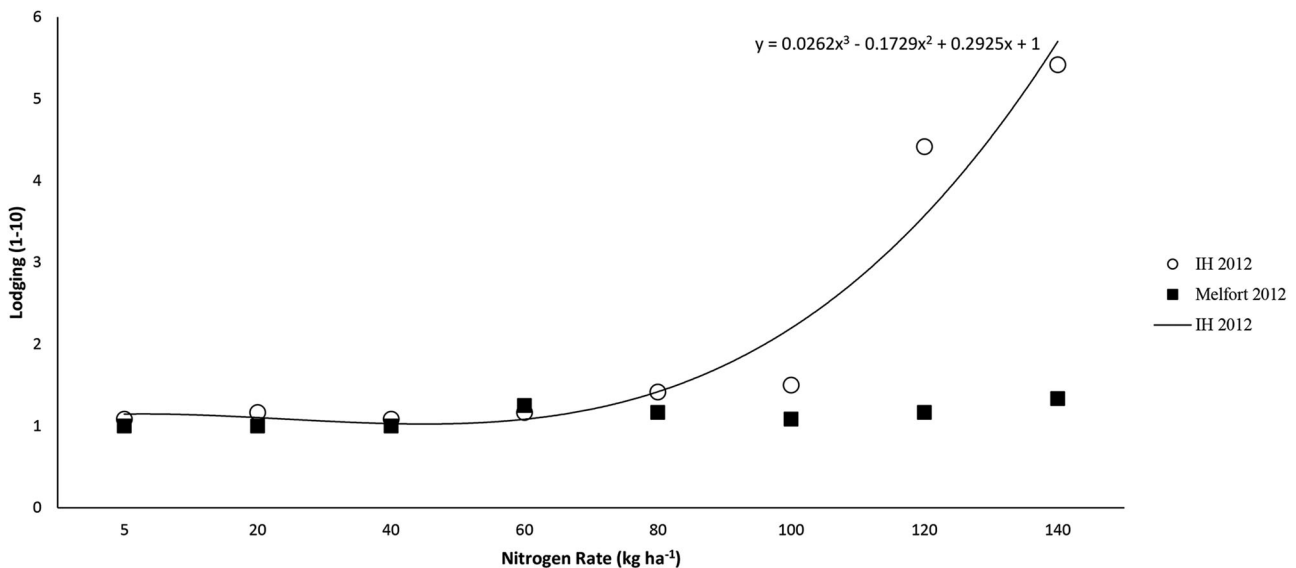
The application of a fungicide reduced leaf disease on the flag leaf at the two locations, Melfort 2012 and Indian Head, 2013, with slightly higher levels of leaf disease compared to the other two site-years (Table 4). At Melfort in 2012 both pyraclostrobin and propiconazole + trifloxystrobin decreased leaf spot infection on the flag leaf, while at Indian Head in 2013, only propiconazole + trifloxystrobin reduced leaf disease severity on the flag leaf. Penultimate leaf disease severity was lowered by the application of a fungicide at three

TABLE 2 Analysis of variance for oat data collected at two sites: Indian Head and Melfort in 2012 and 2013

Effect	P-value	Plant density		Panicle density		Height cm	Lodging 1–9	Leaf disease flag		Leaf disease flag –1 Grade %	Yield Kg ha ⁻¹	Test weight g 0.5 L ⁻¹	Kernel weight g 1000 k ⁻¹	Plump seed %	Thin seed %	Oat groat %
		Plant m ⁻²	Panicle m ⁻²	Leaf disease Grade %	Leaf disease Grade %											
Fungicide (F)	N/A	0.443	0.335	0.304	0.397	0.004	<.001	0.004	<.001	0.325	0.169	<.001	0.049	0.256	0.038	0.766
Nitrogen rate (N)	0.382	0.000	0.000	0.000	0.000	0.017	0.000	0.022	<.001	<.001	<.001	<.001	0.007	<.001	<.001	0.068
Linear	0.642	0.158	0.594	0.000	0.000	0.115	0.000	0.074	0.004	0.000	0.000	0.000	0.144	0.000	0.000	0.576
Quadratic	0.314	0.147	0.158	0.011	0.073	0.674	0.911	0.410	0.159	0.958	0.556	0.216	0.659	0.792	0.792	0.064
Cubic	N/A	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.170	0.351	0.120	0.494
F × N	<.001	0.239	0.041	0.099	0.217	<.001	<.001	<.001	<.001	0.001	0.246	0.391	0.600	0.405	0.405	0.128
Site (S)	N/A	0.255	0.041	<.001	<.001	0.491	0.755	0.087	0.000	0.114	0.005	0.018	<.001	<.001	0.001	0.206
S × F	0.024	0.168	0.001	0.000	<.001	0.087	0.000	0.106	0.000	0.000	0.000	0.157	0.000	0.000	0.000	0.533
S × N	0.964	0.335	0.746	0.000	<.001	0.106	0.514	0.452	0.107	0.000	0.000	0.014	0.139	0.140	0.028	
Indian Head, 2012	0.131	0.964	0.746	0.443	0.106	0.452	0.106	0.996	0.039	0.000	0.030	0.419	0.784	0.607	0.113	
Linear	0.580	0.000	0.000	0.000	.	0.996	0.039	0.272	0.073	0.000	0.288	0.295	0.559	0.221	0.001	
Quadratic	0.150	0.085	0.480	0.003	.	0.501	0.440	0.501	0.440	0.257	0.715	0.970	0.298	0.500	0.005	
Cubic	0.618	0.000	0.000	0.000	0.776	0.014	0.014	0.014	0.014	0.000	0.052	0.796	0.247	0.001	0.000	
Melfort 2012	0.382	0.743	0.318	0.033	0.855	0.444	0.019	0.444	0.235	0.254	0.251	0.515	0.505	0.376	0.206	
Linear	0.321	0.000	0.318	0.347	0.455	0.702	0.235	0.702	0.235	0.938	0.432	0.448	0.463	0.849	0.651	
Quadratic	0.144	0.000	0.000	0.000	.	0.030	0.039	0.030	0.039	0.000	0.019	0.000	0.000	0.002	0.494	
Cubic	0.180	0.742	0.318	0.062	.	0.812	0.230	0.812	0.230	0.135	0.306	0.190	0.385	0.800	0.034	
Melfort, 2013	0.140	0.106	0.106	0.312	.	0.195	0.530	0.195	0.530	0.950	0.280	0.454	0.691	0.900	0.165	
Linear	N/A	0.489	0.489	0.830	0.948	0.548	0.657	0.548	0.657	0.954	0.980	0.223	0.885	0.685	0.561	
Quadratic																
Cubic																
S × F × N																

TABLE 3 Response of panicle density, kernel weight and height to increasing nitrogen rate at Indian Head and Melfort in 2012 and 2013 averaged across the fungicide treatments

Nitrogen rate kg N ha ⁻¹	Panicle density				Kernel weight				Height			
	2012		2013		2012		2013		2012		2013	
	Indian	Melfort	Indian	Melfort	Indian	Melfort	Indian	Melfort	Indian	Melfort	Indian	Melfort
	Head	Head	Head	Head	Head	Head	Head	Head	Head	Head	Head	Head
	Panicles m ⁻²				g 1000 kernels ⁻¹				cm			
5	371	302	303	355	30.5	35.6	35.1	37.4	85	102	103	111
20	374	282	328	347	31.0	35.8	35.5	36.8	89	105	109	114
40	374	298	329	355	30.8	35.6	35.4	36.2	99	110	113	119
60	366	330	335	376	31.6	35.0	35.6	35.8	104	113	114	122
80	396	332	343	398	31.2	35.6	36.3	35.4	107	115	115	126
100	387	344	347	410	31.2	35.5	35.2	35.0	109	116	115	125
120	403	341	345	417	30.5	36.2	35.9	35.7	112	117	118	124
140	410	355	348	428	28.8	35.5	35.4	34.7	112	120	119	129
SE	11	12	9	28	0.76	0.44	0.4	0.5	1.1	1.5	1.1	2.1
Intercept	364.1	288.2	314.9	340.2	30.1	NS	NS	37.1	74.6	97.8	94.8	110.6
x coefficient	0.298	0.495	0.281	0.643	0.0469	NS	NS	-0.0170	9.72	4.45	10.36	2.39
x ² coefficient	NS ^a	NS	NS	NS	-0.0004	NS	NS	NS	-0.636	-0.225	-1.856	NS
x ³ coefficient	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.1174	NS

^aNS, not significant.**FIGURE 1** Response of lodging to increasing nitrogen rate showing the interaction of site and nitrogen rate at four site-years. The LSD_{.05} was 0.942 for Indian Head (IH) 2012 and 0.292 for Melfort 2012. The standard error at Indian Head was 0.34 in 2012

of the four locations. At Melfort in 2012, the application of propiconazole + trifloxystrobin lowered the level of leaf disease, and pyraclostrobin reduced leaf disease to a lower level than propiconazole + trifloxystrobin. At Indian Head in 2013 both fungicide treatments decreased leaf disease on the penultimate leaf compared to the no fungicide treatment. At Melfort in 2013 pyraclostrobin reduced the leaf disease on the penultimate leaf compared to the no fungicide treatment.

In an earlier study, pyraclostrobin reduced leaf disease on the flag and penultimate leaf when leaf disease was at this low level of severity (May et al., 2014). Dietz et al. (2019) in a year with a low level of disease severity was unable to lower the disease severity with a fungicide application. As expected when disease severity is moderate to high, fungicides are effective in reducing disease severity in oat (Dietz et al., 2019; May et al., 2014).

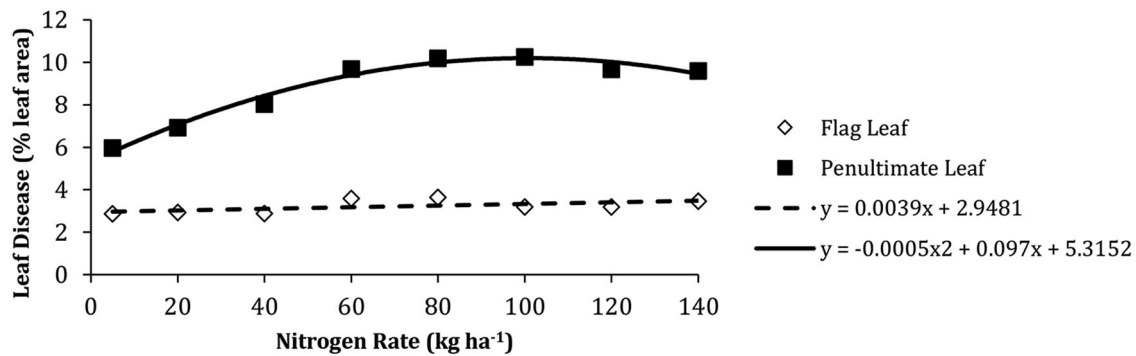


FIGURE 2 Response of leaf disease on flag and penultimate leaves to increasing nitrogen rates. The standard error of the flag leaf was 0.23 and it was 0.90 for the penultimate leaf

TABLE 4 Effect of site and fungicide application on the growth of oat and the severity of leaf disease

Year/fungicide	Leaf disease		Grain yield t ha ⁻¹
	Flag leaf % leaf area	Penultimate leaf % leaf area	
2012			
Indian Head			
No Fungicide	2.30 a ^a	5.33 a	4.79 a
Pyraclorobin	2.41 a	5.10 a	4.73 a
Propiconazole + trifloxystrobin	2.19 a	4.66 a	4.64 a
LSD	0.43	1.96	0.19
Melfort			
No Fungicide	4.35 a	17.65 a	5.53 a
Pyraclorobin	2.96 b	3.76 c	5.15 b
Propiconazole + trifloxystrobin	3.23 b	8.30 b	5.31 ab
LSD	0.62	2.64	0.27
2013			
Indian Head			
No Fungicide	5.07 a	10.91 a	7.40 b
Pyraclorobin	4.02 ab	7.64 b	7.81 a
Propiconazole + trifloxystrobin	3.53 b	6.95 b	7.59 ab
LSD	1.09	3.19	0.25
Melfort			
No Fungicide	3.21 a	14.77 a	7.24 a
Pyraclorobin	2.58 a	8.18 b	7.13 a
Propiconazole + trifloxystrobin	2.79 a	12.29 ab	6.93 a
LSD	0.73	4.15	0.41

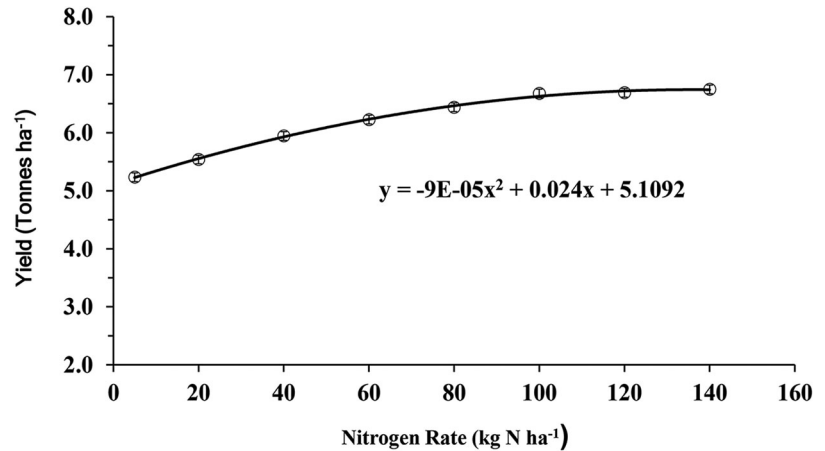
^aValues within columns by site-year followed by a common letter are not significantly different at the .05 probability level.

3.5 | Maturity and kernel weight

Maturity was affected by site, N rate, and site × N rate but was not affected by fungicide application (data not shown). Melfort 2012 tended to have a later maturing crop compared to other site-years and maturity remained constant across all N rates while all other sites had a linear delay in maturity from 1 to 4 d as the N rate increased (data not shown).

Kernel weight was affected by fungicide, N rate, site, and site × N rate (Table 2). The kernel weight when no fungicide was applied was 34.0 g 1000 kernels⁻¹. The application of pyraclorobin increase kernel weight to 34.4 g 1000 kernels⁻¹ (LSD_{.05} = 0.4) while the application of propiconazole + trifloxystrobin increased kernel weight to 34.9 g 1000 kernels⁻¹ (LSD_{.05} = 0.4). Similarly, May et al. (2014) observed an increase in kernel weight in one out of four

FIGURE 3 Response of grain yield to increasing nitrogen rates averaged over fungicide treatments over four site-years. The standard error is 0.15



cultivars when disease levels were low to moderate. Indian Head, 2012 had lower kernel weights than other site-years and followed a quadratic trend as N rate increased (Table 3). This decrease in kernel weight at Indian Head in 2012 is probably linked to the increased lodging that occurred at the high N rates. At Melfort in 2012 and Indian Head in 2013 kernel weight remained stable and was not affected by N rate, while at Melfort in 2013 kernel weight decreased as the N rate increased. Other studies have shown a consistent decrease in kernel weight as the N rate increased (Lafond et al., 2013; Mohr et al., 2007; Pecio & Bichoniski, 2010). This decrease in kernel weight as N rate increases is probably due to the fact that kernel weight is the last yield component of oat. As the N rate is increased plant density, panicle density and seed density usually increase under good growing conditions. Often the growing conditions between anthesis and physiological maturity reduce the yield potential of the oat and the only adjustments the crop can make are abortion of flowers or seed and a reduction in kernel size, with kernel size being the more sensitive adjustment to determine final grain yield.

3.6 | Grain yield

Grain yield was affected by N rate, site, and site \times fungicide (Table 2). As the N rate increased there was a curvilinear increase in grain yield (Figure 3). Oat was highly responsive to increasing fertilizer N at low rates but less responsive to higher N rates. Grain yield continued to increase to the highest N rate (140 kg ha⁻¹) but began to flatten out at 100 kg ha⁻¹ increasing from 6.63 to 6.74 t ha⁻¹ at 140 kg ha⁻¹. Grain yield was high at both locations in 2013 compared to 2012. Previous research often found oat had a lower N response than measured in this study. May et al. (2004) found that one cultivar had a linear increase in grain yield as the N fertilizer rate increased from 5 to 120 kg N ha⁻¹ while another cultivar had a curvilinear increase that peak around 80 kg N ha⁻¹. In a Manitoba study, two site-years required 40 kg N ha⁻¹

and two other site-years required 120 kg N ha⁻¹ to maximize yield (Mohr et al., 2007). Lafond et al. (2013) found that a maximum yield was achieved at 60 kg N ha⁻¹. The N response in this study was similar to other studies but the responsiveness to N rate appears to be more consistent in the current study compared to previous research. This likely reflects ample moisture conditions in the current study.

The response of grain yield from a fungicide application was inconsistent. An application of pyraclostrobin increased grain yield at one out of the four site-years, Indian Head in 2013, and decreased grain yield at one out of the four site-years, Melfort 2012 (Table 4). An application of propiconazole + trifloxystrobin had no effect on grain yield. These responses are not enough to support a fungicide application as Triactor is a moderately resistant cultivar. Application of fungicide did not benefit the grain yield at the disease levels measured in this experiment. This is supported by Sooväli et al. (2010), they found at low to moderate disease severity of crown rust and leaf disease a fungicide application prevented the increase in disease severity but had little effect on grain yield. Dietz et al. (2019) reported a grain yield response in a year with higher disease severity and no response in a year with low disease severity. Other studies have found a larger response to fungicides with Mourtzinis et al. (2015) finding that an application of pyraclostrobin increased seed yield especially when more susceptible cultivars were included in the study. May et al. (2014) found that as cultivar susceptibility to leaf disease increased and disease severity increased, the benefit of a fungicide increased. The cultivar with good disease resistance to leaf disease derived no benefit from an application of pyraclostrobin. Since crown rust resistance is a major focus of oat breeding programs in North America, it would be interesting to determine the level at which leaf diseases other than crown rust need to reach before fungicide applications become economic. In the current study, no benefit from a fungicide application was noted in the presence of low leaf disease intensity with a cultivar with good resistance to the leaf disease.

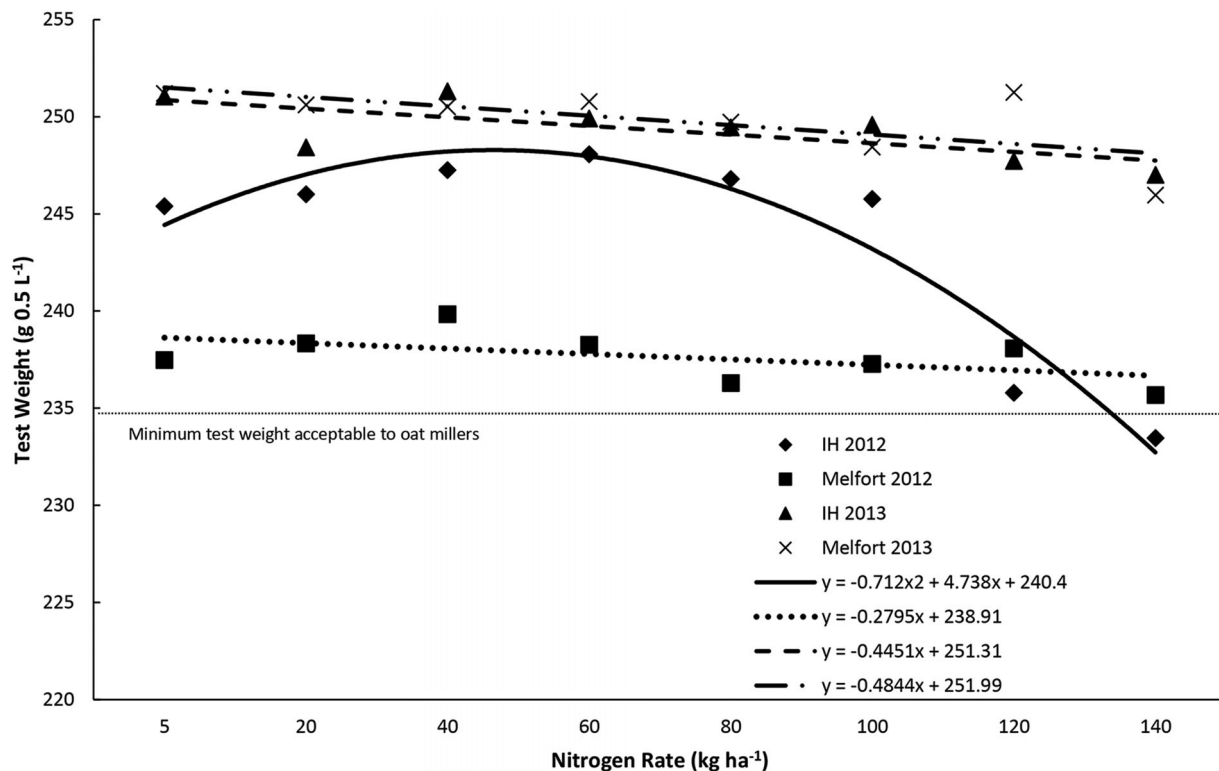


FIGURE 4 Response of test weight to increasing nitrogen rate showing the interaction of site and nitrogen rate at four site-years. The standard error at Melfort was 1.1 in 2012 and 1.3 in 2013 and at Indian Head it was 2.2 in 2012 and 1.4 in 2013

The lack of an interaction of N rate \times fungicide has been observed in other research (Pecio & Bichoniski, 2010; Sooväli et al., 2010). These three studies together provide a strong indication that in oat, fungicides are not providing an additional benefit to plant growth and grain yield besides protecting the plant from leaf diseases as has been claimed in the past (BASF 2009). Under high disease pressure, it is thought that there would be an interaction between N and fungicide as an increasing N rate would increase the amount of leaf tissue that a fungicide could protect. Dietz et al. (2019) had 1 yr with low disease pressure and 1 yr with high disease pressure; however, the year \times N rate \times fungicide interaction was not significant for grain yield while N and fungicide were both highly significant as main effects. Unfortunately there were only two N levels which make detection of a differential N response at different levels of disease severity between years and fungicide treatment very difficult. The current research including the results from this study strongly indicate that for grain yield, management decisions on the appropriate N rate and the use of fungicides can be made independently of each other.

3.7 | Test weight

Test weight was affected by N rate, site, and site \times N rate but not by fungicide application (Table 2). At three site-years, Melfort, 2012, Melfort, 2013, and Indian Head 2013 there

was a small linear decrease in test weight as the N rate increased (Figure 4). The decrease was so small that the decrease would not have lowered the acceptability of the oat to the milling industry except possibly at Melfort 2012. At Melfort in 2012 the test weight was under 340 g 0.5 L⁻¹ and the minimum acceptable to most oat millers is 235 g 0.5 L⁻¹. The response at these three site-years is supported by other research studies (Browne et al., 2003; Lafond et al., 2013; Mohr et al., 2007). At Indian Head in 2012 there was a curvilinear decrease in test weight as the N rate increased. The decrease from a test weight above 245 g 0.5 L⁻¹ to a level below 235 g 0.5 L⁻¹ at Indian Head in 2012 corresponded to an increase in lodging that occurred as the N rate increased from 100 to 140 kg ha⁻¹ (Figure 1). In an earlier study with two cultivars, the cultivar with the greatest increase in lodging as the N rate increased had the greatest decrease in test weight as the N rate increased (May et al., 2004). It would be interesting to explore the site \times N effect on test weight by examining the changes in spikelets per panicle, mass of primary, secondary and tertiary kernels per spikelet and how the differences change the packing density of the oat kernels at sites where test weight is sensitive to N rate and where it is not. This may allow us to better predict when oat producers need to use caution when using higher N fertilizer rates.

Test weights ranged between 244 and 246 g 0.5 L⁻¹ with fungicide applications showing no significant differences

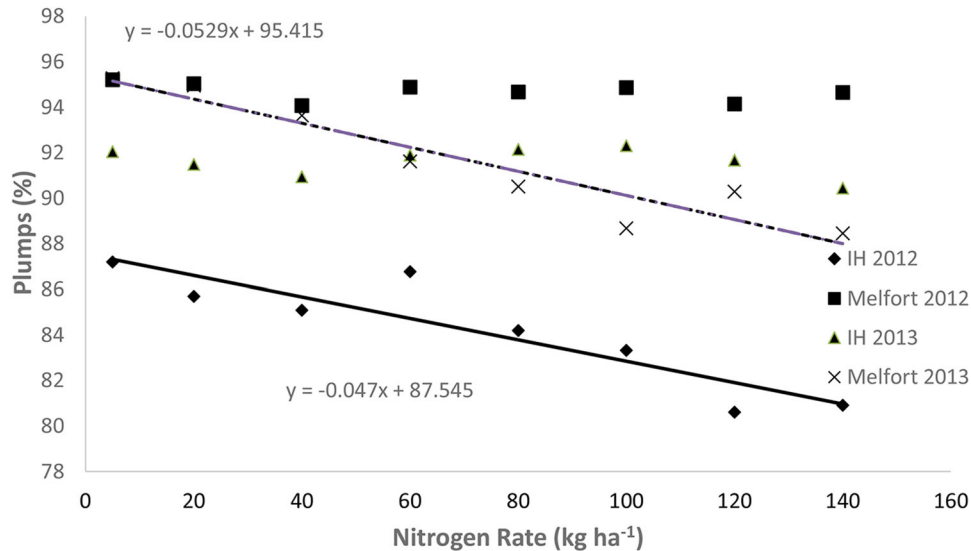


FIGURE 5 Response of percentage plumps in yield to increasing nitrogen rate showing the interaction of site and nitrogen rate at four site-years. The standard error at Melfort was 0.40 in 2012 and 1.4 in 2013 and at Indian Head it was 0.84 in 2012 and 0.76 in 2013

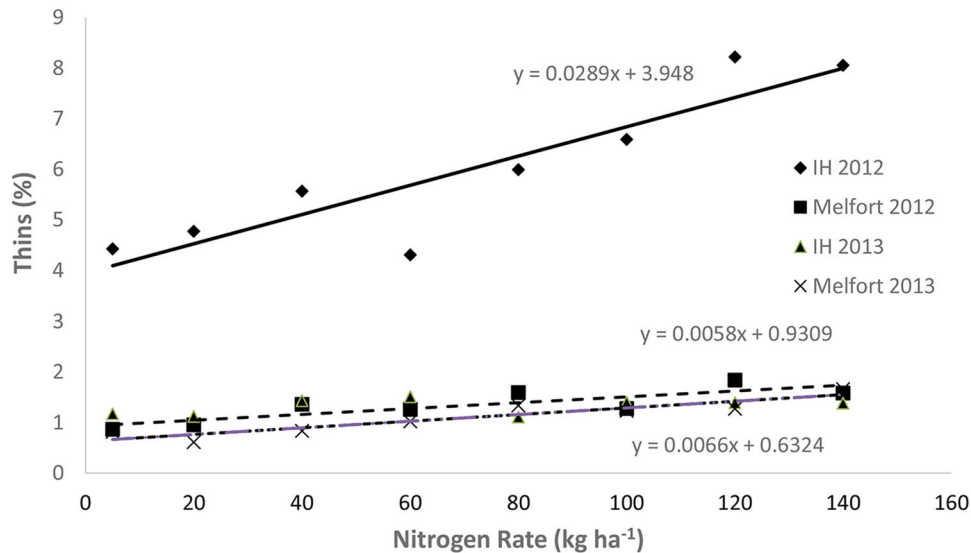


FIGURE 6 Response of percentage thins in yield to increasing nitrogen rate showing the interaction of site and nitrogen rate at four site-years. The standard error at Melfort was 0.21 in 2012 and 0.24 in 2013 and at Indian Head it was 0.60 in 2012 and 0.14 in 2013

between fungicides and no fungicide. This response is supported by previous research that found at low disease intensity with resistant cultivars an application of pyraclostrobin did not improve test weight (May et al., 2014). It should be remembered that at high levels of disease severity an effective fungicide application will protect test weight and reduce any reduction in test weight (Federizzi et al., 2015; May et al., 2014; van Niekerk et al., 2001).

3.8 | Plump seed and thin seed

Plump seed was affected by site, N rate, and site \times N rate but not by fungicide (Table 2). At Indian Head in 2012 and

Melfort in 2013 there was a linear decrease in plump seed as the N rate increased (Figure 5). Nitrogen rate had no effect on plump seed at Melfort in 2012 and Indian Head in 2013. This result is supported by previous research (Lafond et al., 2013; May et al., 2004; Mohr et al., 2007). Fungicide application did not affect percentage of plump seed, with percentages ranging between 90 and 91 for the fungicide treatments.

Percentage of thin seed was affected by fungicide, site, N rate, and site \times N rate (Table 2). Three of four site-years saw a linear increase in thin seed as N rate increased. Indian Head, 2012 had higher percentage of thin seeds compared to other site-years and also saw a more drastic increase in thin seed; climbing to 8% at the 140 kg N ha⁻¹ rate (Figure 6). Millers will not usually accept oat that has 10% of more thin

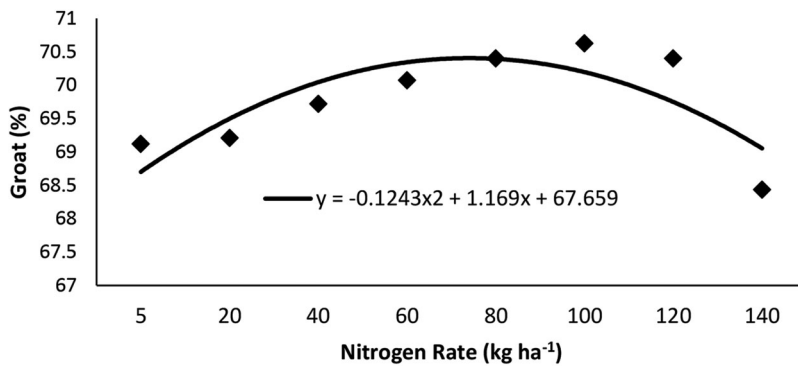


FIGURE 7 Response of groat percentage in oat kernels to increasing nitrogen rates. The standard error is 0.58

seed. The 8% thin seed probably would reduce the price that the grower would receive from an oat miller for his grain. Fungicide application affected percentage of thin seed as the no fungicide treatment had a higher percentage (2.7%) of thin seed than pyraclostrobin (2.3%) or propiconazole + trifloxystrobin (2.3%) ($LSD_{.05} = 0.2$). Both pyraclostrobin and propiconazole + trifloxystrobin had the same average percentage of thin seed.

3.9 | Groat percentage

Groat percentage was only affected by site (Table 2). Groat percentage at Indian Head in 2012 at 67%, was lower than the groat percentage at the other three sites which ranged from 70 to 71% ($LSD_{.05} = 1$) (data not shown). These differences were likely a result differing weather conditions between years and sites. Fungicide application did not affect groat percentage.

Increasing the N rate had a quadratic effect on groat percentage peaking at 100 kg ha⁻¹ of N then drastically dropping as the N rate increased from 120 to 140 kg N ha⁻¹ (Figure 7).

3.10 | Economics of nitrogen fertilizer rate

To examine the economics of the N rate response curve for this study, the economic return generated by each N rate compared to the lowest N rate, 5 kg ha⁻¹, was calculated and presented in Figure 8. For each of the nine combinations there was a significant quadratic contrast as the N rate increased with a p -value <.001 for each combination. At a low value for oat of \$130 t⁻¹ (Figure 8a) the best N rate is very sensitive to the price of N. When the N price is \$1 kg⁻¹ a rate of 100 kg N ha⁻¹ provided the greatest return and as the cost of N increased the N rate that provided the greatest return drop to between 60 and 80 kg ha⁻¹ at \$1.5 kg of N and 40 kg ha⁻¹ at

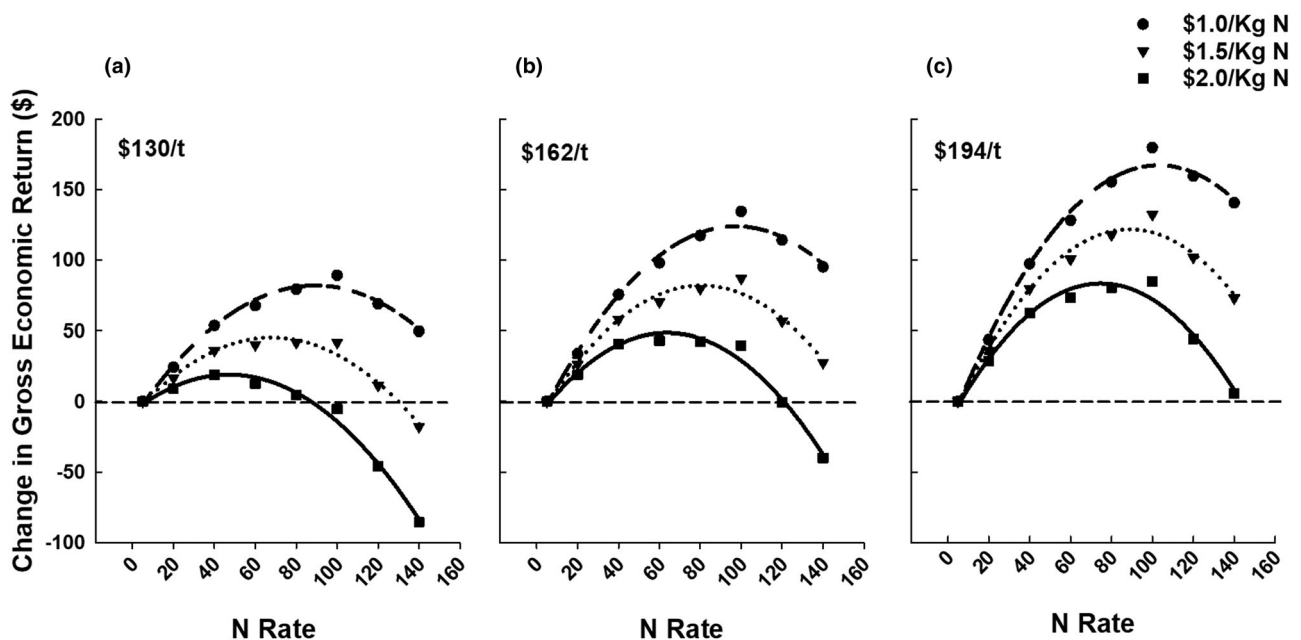


FIGURE 8 Change in gross returns compared to 5 kg N ha⁻¹ as the nitrogen (N) rate increased at three grain prices and three nitrogen prices over all sites and years for the nitrogen experiment. The p -value for all the quadratic orthogonal contrasts were <.001 and the standard error was 14.7 for a, 18.2 for b and 21.8 for c

\$2 kg⁻¹. As the crop price increased to \$162 t⁻¹ (Figure 8b) and \$194 t⁻¹ (Figure 8c) the optimum rate increased to 100 kg ha⁻¹ except when the price of N was \$2 kg⁻¹. At an N price of \$2 kg⁻¹ the optimum N rate was 60 kg N ha⁻¹ when the oat price was \$162 t⁻¹ and 80 kg N ha⁻¹ when the oat price was \$194 t⁻¹. In general, as the oat price increased the impact of N cost decreased, reducing the economic risk from high N rates; however, in this study there were negative impacts on grain quality from the increase N rate, lowered test weight, increased thin seed, and lodging. Lodging that individual producers experience in their own producer fields may be the largest hindrance for many oat growers in using a higher N rate. As demonstrated at Indian Head in 2012 significant levels of lodging can reduce yield and quality reducing both the amount of grain available for sale and the price of the crop being sold. This may lead many growers to use a lower N rate than found to be optimum for grain yield to reduce the risk they assume when growing an oat crop.

4 | CONCLUSION

No interaction between fungicide and N was observed. These results combined with results from other studies (Dietz et al., 2019; Pecio & Bichoniski, 2010; Sooväli et al., 2010) indicate that growers can treat these management practices independent of one another. Disease was not high enough to effect grain yields significantly, and fungicide showed no benefits to improve key quality variables such as test weights and groat percentage. Lodging increased with higher N rates overall resulting in lower test weights as seen in previous studies. Cultivar resistance was moderate and leaf spot diseases remained low but were shown to increase with higher N rates. Nitrogen rates significantly increased grain yield as the N rate was increased from 15 to 140 kg ha⁻¹. At a low price of oat, \$130 t⁻¹, the N rate that maximized economic return was very sensitive to the price of N fertilizer. As the crop price increased the optimum N rate was 100 kg ha⁻¹ except at \$2 N ha⁻¹. There were small negative impacts on grain quality at this rate; however, the decrease in quality observed in this study would probably not be enough to affect the economic returns received by the producer except at Indian Head in 2012. Lodging may be a limitation on producers implementing this N rate. In conclusion, our results indicate that using an N rate of 100 kg ha⁻¹ provided the most consistent economic returns when the crop price is between \$162 and \$194 t⁻¹ and that there is no beneficial interaction between fungicide and N for growers using higher N rates.

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