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ARTICLE

Nitrogen management strategies on plant growth and severities of *Sclerotinia* stem rot of canola in eastern Canada

Fen Gao, Yuanhong Chen, SeaRa Lim, Allen G. Xue, and Bao-Luo Ma

Abstract: Effective nitrogen (N) management strategies are important for ensuring a balance between optimizing plant growth and minimizing disease damage. A field experiment was conducted for three years to (*i*) assess the effects of N fertilizer application on the growth and seed yield of canola and severities of *Sclerotinia* stem rot (SSR), and (*ii*) to determine a reasonable N-rate for optimizing plant growth and minimizing the loss from SSR in eastern Canada. The experiment was designed with factorial combinations of eight N treatments and two canola hybrids. All N treatments reduced canola emergence with increasing preplant N application rates above 100 kg ha^{-1}, but had a positive impact on plant height, fresh weight, dry weight, and seed yield. The development of SSR showed differential responses to N application rates. Of all the treatments, the split application (50 kg N ha^{-1} at preplant plus 100 kg N ha^{-1} side-dressed at the 6-leaf stage) increased canola growth and often produced the highest or similar seed yields to those of equivalent N rate applied as preplant. At the 150 kg ha^{-1} N rate, no severe development of SSR was observed in either preplant-only or split application. Overall, this study demonstrates that the split-N management strategy (50 + 100 kg ha^{-1}) maintained a balance between enhancing plant growth and mitigating the negative impacts of SSR on canola.

Key words: canola, *Brassica napus*, *Sclerotinia* stem rot, *Sclerotinia sclerotiorum*, plant growth, N-fertilizer management.

Résumé : Nul ne niera l'importance d'une stratégie efficace de gestion de l'azote (N) pour atteindre l'équilibre entre une croissance optimale de la plante et les plus faibles dommages possibles attribuables à la maladie. Pendant trois ans, les auteurs ont poursuivi une expérience sur le terrain pour, d'une part, évaluer les effets d'un engrais N sur la croissance et le rendement grainier du canola ainsi que la gravité de la pourriture sclérotique du colza (PSC) et, d'autre part, déterminer un taux d'application raisonnable du N qui optimiserait la croissance de la culture tout en minimisant les pertes causées par la PSC, dans l'est du Canada. Ils ont conçu leur expérience en combinant de façon factorielle huit régimes de fertilisation et deux hybrides du canola. Tous les régimes de fertilisation ont réduit la levée du canola quand le taux d'application de l'engrais N avant les semis dépassait 100 kg par hectare, mais ont aussi eu un effet positif sur la taille du plant, le poids frais, le poids sec et le rendement grainier. La PSC réagit différemment au taux de fertilisation. Parmi les traitements, l'application fractionnée (50 kg de N par hectare avant les semis et le double, épandu en bandes latérales au stade de la sixième feuille) améliore la croissance du canola et engendre souvent un rendement grainier supérieur ou similaire à celui obtenu avec l'application d'une quantité identique d'engrais N, avant les semis. L'application de 150 kg de N par hectare empêche un développement sérieux de la PSC, que l'engrais soit épandu en entier avant les semis ou de façon fractionnée. En général, cette étude révèle que l'application fractionnée d'engrais N (50+100 kg par hectare) préserve l'équilibre entre la croissance de la plante et la lutte contre la SPC chez le canola. [Traduit par la Rédaction]

Mots-clés : canola, *Brassica napus*, pourriture sclérotique du colza, *Sclerotinia sclerotiorum*, croissance végétale, gestion des engrais azotés.

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Introduction

Canola (*Brassica napus* L.), a high-value crop of healthy oil and animal meal protein, as well as a viable renewable feedstock for biofuel production, has become the dominant field crop in the Canadian Prairies, with >8 million ha under canola production in 2016, surpassing common spring wheat (Ma et al. 2019). Nitrogen (N) is both an indispensable element of plant growth and development and an important constituent of grain protein (Singh et al. 2019). Several studies have been conducted on the effects of N fertilization on canola nutrient uptake, nutrient balance, and canola yields (Ma and Herath 2016; Ma et al. 2015, 2019, 2020; Singh et al. 2019). In eastern Canada, sound agronomic practices have recently been developed for canola production, particularly with respect to N fertilizer application and improved N-use efficiency for the environmental and economic sustainability of canola production (Ma et al. 2015; Ma and Herath 2016; Ma et al. 2019).

N fertilizer application also affects the development of plant diseases in crops. The increase in disease severity was found to be correlated with N fertilizer application in some pathosystems: an increase in N-rate resulted in an increased crown rot (*Fusarium pseudograminearum* O'Donnell & T. Aoki) (Smiley et al. 1996) and scab (*Fusarium* spp.) (Liu et al. 2015) in wheat, or blast (*Magnaporthe grisea*) in rice (Talukder et al. 2005). The effect of N-rate appeared to be highly pathogen-dependent, because of the differences in response to nutrient supply among various pathogens, especially between the obligate and facultative parasite (Huber et al. 2012). With increasing N application rates, the disease incidence increased and tomato plants were infected by powdery mildew (*Oidium lycopersicum*) and leaf spot (*Pseudomonas syringae* van Hall), decreased by gray mold (*Botrytis cinerea* Pers.), and remained unaffected by wilt (*Fusarium oxysporum* Schltdl.) (Hoffland et al. 1999, 2000). In addition, the levels of disease development resulting from N fertilizer application could vary with crop varieties and plant growth conditions. Pumphrey et al. (1987) reported that neither time nor the rate of N application had a significant effect on the occurrence of winter wheat (cv. Stephens) patch caused by *Rhizoctonia solani* Kühn in Hermiston (Adkins loamy sand), USA. MacNish (1985) found that N fertilizer reduced *Rhizoctonia* patch of wheat (cv. Madden) under zero-tillage in Esperance (sandplain soil), Australia.

Sclerotinia stem rot (SSR), caused by *Sclerotinia sclerotiorum* (Lib) de Bary, is a destructive disease of canola and poses a serious economic threat to canola production world-wide (Sharma et al. 2015). In Canada, the annual occurrence of SSR is at 10%–20%, equating to an average yield loss of approximately 5%–10% (Derbyshire and Denton-Gile 2016). Canola is a small crop relative to cereals and soybean in eastern Canada, but its importance in promoting complex crop rotation systems has been increasingly recognized by researchers (Ma and Wu 2016; Ma et al. 2020). Therefore, the occurrence and severity of SSR must be investigated to develop a sustainable canola production system for eastern Canada.

There have been studies concerning the effect of N fertilizer on the canola SSR conducted elsewhere in recent years. For example, a field experiment carried out in Hubei, China, showed that the application of N fertilizer increased the SSR disease index by 17.7% (Li et al. 2013). Brandt et al. (2007) reported that the N-rate had no significant impact on SSR incidence in the Parkland region of the Canadian prairies.

In light of the complex responses and significant spatial variability of SSR to N fertilizer, a reasonable N management that considers the synergistic interactions and balance between nutrient requirements of the crop and the disease occurrence is even more imperative to improving canola yields. Up to date information is still lacking regarding optimal and comprehensive management practices that stress the effects of N-rate on canola production as well as on SSR in eastern Canada, although the recommended N-rates have provided the regional or site-specific guidelines for higher canola yield and environmentally-sound N management (Ma and Herath 2016; Ma et al. 2015, 2019, 2020). The objectives of the present study were to (*i*) understand the effects of N fertilizer on canola growth parameters, seed yield, and development of SSR, and (*ii*) determine a reasonable N-rate for making improved N management decisions in eastern Canada. The results can help to find the balance of N requirements between higher canola yields and lower SSR disease severity, and further optimize the economic and environmental benefits.

Materials and Methods

Experimental site and design

The field experiments were conducted at Central Experimental Farm of Agriculture and Agri-Food Canada (AAFC), Ottawa, ON (45°23′N, 75°43′W) in 2014, 2015, and 2016. The soil type was sandy loam. The daily precipitation and temperature in the experimental growing seasons are given in Fig. 1. Moderate levels of SSR were observed in the preceding soybean crop in 2013, and the disease was not found in the preceding crops of oat in 2014 and spring wheat in 2015 at the experimental site. Other agroclimatic conditions, tillage, and cultural practices at the test site were described in detail by Ma et al. (2019).

The experiment was a randomized complete block design with four replications in each year to test two factors (N treatment and canola hybrid Variety) as an 8×2 factorial arrangement. The eight N treatments as combinations of N-rates and application timing were: 0 (N0), 50 (N50), 100 (N100), 150 (N150), and 200 (N200) kg ha^{-1} at preplant; and 50 kg ha^{-1} at preplant plus 50 (N50 + 50), 100 (N50 + 100), or 150 (N50 + 150) kg ha^{-1} side-dressed

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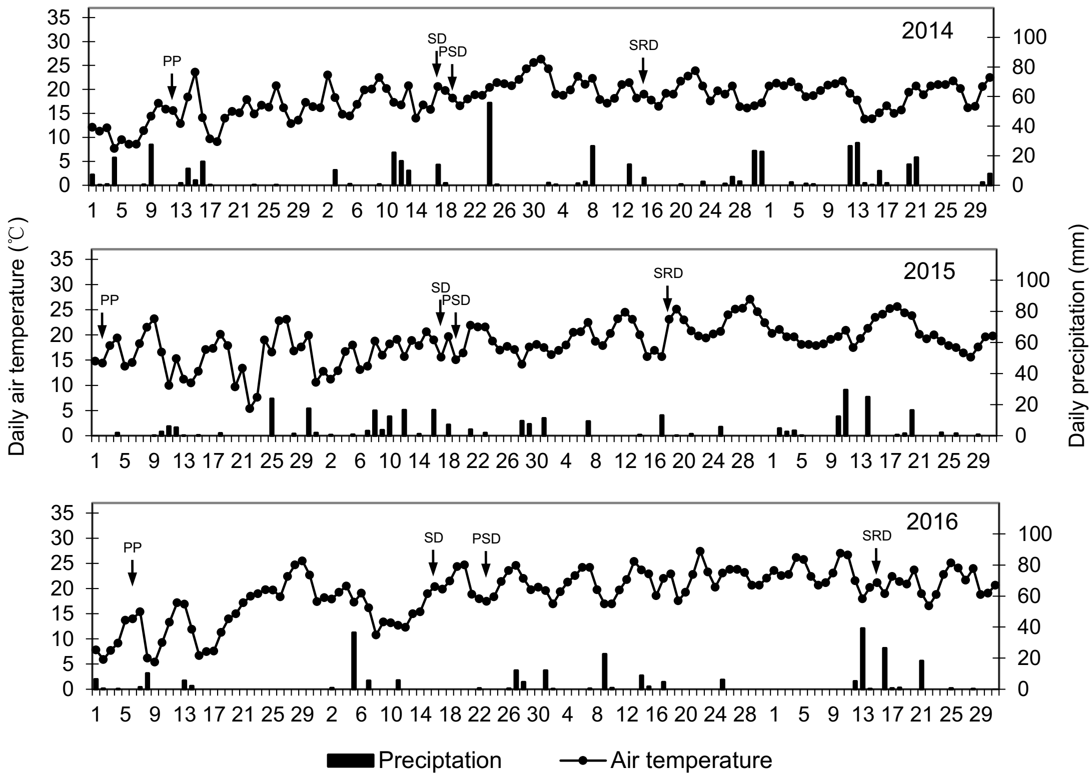
Fig. 1. Daily mean air temperature and precipitation from 1 May to 31 Aug. in Ottawa, Ontario, in 2014, 2015, and 2016. Data were collected by Environment Canada weather station. PP = preplant; SD = side-dressed; PSD = plant sample date for growth parameters; SRD = *Sclerotinia* stem rot rating date.



at the 6-leaf stage of canola. Fertilizer urea was used as the N source. The canola varieties consisted of *Brassica napus* L. hybrid InVigor 5440 and InVigor L140P (except for InVigor L150 in 2014). Both varieties had similar final plant heights and similar phenology within a growing season. They were susceptible to SSR based on our field observations.

The plot was 10 m in length and trimmed to 8 m after full emergence. It contained 12 rows of canola with a row spacing of 19 cm. The trial was sown at the recommended seeding rate of 5 kg ha^{-1} with seeding depth of about 1–2 cm (Ma et al. 2016), on 12 May 2014, 2 May 2015, and 6 May 2016. The final plant density was 80 to 120 plants m^{-2}. Liberty herbicide (2.5 L ha^{-1}) was applied at the 2–4 leaf growth stage of canola for weed control each year. The N fertilizer at preplant was incorporated into the soil on or one day before the planting dates, while side-dressed N was applied manually when the plants reached the 6th fully expanded leaf stage, which occurred on 17 June 2014 and 2015, and 16 June 2016 (Fig. 1).

Sampling and data collection

The plant growth data were collected from rows 3–8 of each plot. Plant emergence was recorded after full emergence in early June each year. The emergence rate (%) = number of plants emerged/total seeds sown in the area × 100. Plant samples (10 seedlings in each plot) were taken shortly after side-dressing N on 19 June 2014 and 2015, and on 23 June 2016 (Fig. 1) for the assessment of plant height, fresh weight, and dry weight. The samples were dried in a forced-draft oven at 80 °C for 3 d. Seed yields were determined by combining a 6-row area in each plot and reported on a 100 g kg^{-1} moisture basis. In 2014, the canola hybrid Invigor 5440 and InVigor L150 were tested; then hybrid Invigor L150 was replaced with L140P in 2015 and 2016. The reason for switching the hybrids was that L150 was more prone to lodging (Wen et al. 2021).

The percentage of plants infected with SSR were counted based on approximately 500 plants in a 5 m × 6 row area from the left front of each plot on 15 July 2014, 18 July 2015, and 15 August 2016 when plants were at the seed development stage (Fig. 1).

The SSR disease incidence (DI_{SSR}) is expressed as follows:

$$DI_{SSR}(\%) = \frac{A}{B} \times 100$$

Where A and B represent the number of plants infected and the total number of plants investigated, respectively.

Statistical analysis

The data of emergence rate, plant height, fresh weight, dry weight, SSR incidence, and seed yield were subjected

Table 1. Mean squares from combined and individual analysis of variance for the effects of N treatment, variety, year, and their interactions on seedling emergence, plant height, fresh weight, dry weight, and seed yield of canola and on disease severity of *Sclerotinia* stem rot (SSR) in Ottawa, Ontario, in 2014, 2015 and 2016.

Components	DF	Emergence (%)	Plant height (cm)	Fresh weight (g/plant)	Dry weight (g/plant)	Seed yield[a] (kg ha^{-1})	SSR (%)
Combined analysis							
Year (Y)	2	9540.5**	2112.9**	11633.3**	106.1*	13006779.2**	1837.0**
Replicate	3	349.8	109.9	436.9	13.4	879861.0	6.9
Error A	6	207.9	94.5	796.2	15.6	119828.3	3.1
Variety (V)[b]	1	6351.5**	693.9**	305.0*	7.5	1197418.5**	7.6
N treatment (N)	7	740.9**	121.1**	1053.5**	8.9**	3274170.1**	35.2**
V*N	7	111.5	26.9	47.1	1.9	577054.5**	20.5
Y*V	2	43.5	90.6	172.8	0.6	2636481.6**	4.5
Y*N	14	113.3	63.0*	146.4**	2.0	984170.8**	48.1**
Y*N*V	14	73.1	58.1*	78.9	3.7	539965.8**	9.7
Error B	135	169.9	32.5	63.4	2.3	75784.9	11.0
Individual analysis							
2014							
Replicate	3	275.3	112.6	173.0	0.2	424286.5	10.4
Variety (V)	1	1914.1**	28.9	554.6**	4.6**	5983981.4**	12.9
N treatment (N)	7	202.5	21.7	260.7**	0.9	861125.2**	91.0*
V*N	7	19.7	18.1	42.6	0.9	1419683.1**	32.0
Error	45	150.4	13.8	58.0	0.5	123111.5	30.1
2015							
Replicate	3	105.0	159.8	1782.0	43.0	105963.0	2.6
Variety (V)	1	2855.6**	252.0*	7.4	3.5	468548.0**	0.4
N treatment (N)	7	535.6	176.8**	981.6**	10.6	2362104.6**	33.4**
V*N	7	179.5	92.3	137.9	8.0	142137.0*	5.4*
Error	45	265.8	48.6	118.6	6.2	50903.2	2.4
2016							
Replicate	3	385.2	26.6	74.4	1.5	589268.1	0.2
Variety (V)	1	1668.7**	594.1**	88.6*	0.5	17852.3	3.3*
N treatment (N)	7	229.3*	48.5	104.0**	1.5**	2019281.9**	7.0**
V*N	7	58.6	32.6	24.4	0.4	95166.0	2.5**
Error	45	93.6	35.2	13.4	0.2	53340.1	0.5

Note: *, ** were significant at $P < 0.05$ and <0.01 levels. DF, degrees of freedom.
[a]This data was originally included in a large data set in a machine learning model to estimate site-specific N recommendations (Wen et al. 2021).
[b]For the yield, the canola hybrid Invigor 5440 and InVigor L150 were tested in 2014; then hybrid Invigor L150 was replaced with L140P in 2015 and 2016.

to analysis of variance without transformation. An individual analysis of variance for each year and a combined analysis over years were conducted using the MIXED procedure in SAS version 9.4 (SAS Institute Inc. Cary, NC, USA) with years and replications as random effects, and N treatment and variety as fixed effects. Treatment means were separated by Fisher's Least Significant Difference (LSD) test at a probability level of $P \leq 0.05$ when ANOVA showed significant treatment effects.

Results and Discussion

The year 2014 had a slightly cold, wet May, with total rainfall of 87 mm and an average temperature of 14.2 °C, and was warm and rainy from June to August. In 2015, the lowest average temperature was 17.2 °C in June and a minimum rainfall of 40.8 mm in July, compared with the same period in 2014 and 2016. In 2016, the weather was warm throughout the growing season; however, it was obviously drier than in 2014 and 2015. The total precipitation was 26.2 mm in May, 66.2 mm in June, much less than in the same periods of 2014 and 2015, and 57.2 mm in July, slightly more than 2015. These data indicated that canola did not encounter extreme climatic conditions that could affect its growth from 2014 to 2016.

Analysis of variance showed that both N treatment and year effects were significant on emergence, plant height, fresh weight, dry weight, seed yield, and SSR incidence. There was a significant N treatment × year interaction on fresh weight, seed yield, SSR incidence, and plant height, indicating that the N treatment had different effects on the above parameters in different years (Table 1). The varieties had varying effects on emergence, plant height, fresh weight, and seed yield. There was a significant interaction of year × variety on seed yield in 2014 and 2015, but not in 2016. The N treatment × year × variety interactions were observed for plant height and seed yield (Table 1).

N fertilizers are essential to increase canola yields by promoting vigorous growth and development, and affecting key yield components as well (Ma et al. 2019). In 2014, the treatments N50, N150, and N200 significantly increased the fresh weight; and no difference showed between N150 and N200, but both were higher than N50 at the 6-leaf stage. With other treatments, including N100, N50 + 50, N50 + 100 and N50 + 150, no significant effects were observed. The main reason why N split application had no effect on increasing fresh weight was because the side-dressed N did not have enough time to affect plant biomass. Another explanation may have resulted from the 13.8 mm precipitation on 17 June (Fig. 1). The rainwater on the day of the side-dressed application of N fertilizer might have washed away part of the fertilizer, resulting in a decrease of N uptake by canola. In 2015, all N treatments significantly increased the fresh weight, and N200 showed a more obvious effect than all the other treatments except N150. In 2016, the effects of all N treatments were consistent with those in 2015 (Table 2).

At 200 kg N ha^{-1}, the fresh weight of preplant treatments was obviously higher than that of split application treatments in all 3 yr. At 150 kg N ha^{-1}, the preplant treatments were significantly higher than split application treatments only in 2014, and there was no difference in 2015 and 2016 (Table 2).

On average across the 3 yr, the canola dry weight increased with N-rates in preplant application but was not significantly affected by the split application. There was a significantly greater dry weight in treatments N100, N150, N200 and N50 + 50 compared with the control N0. N200 was significantly higher than N100 and N50 + 50, while N150 showed comparable improvement effect. The dry weight of preplant N treatment was higher than that of N split application at either a total N-rate of 150 or 200 kg ha^{-1} (Table 2).

Plant height is a good index of the relative growth rate of crops and is an important morphological character related to vegetative growth (Singh et al. 2019). In all 3 yr, plant height positively responded to N applications in most cases; however, the highly significant promoting effects of N treatments were observed only in 2015. Except for N50 and N50 + 150, the remaining treatments significantly increased the plant height in comparison with the control N0; and no difference was observed among them (Table 2). In 2014, treatments N150, N200, and N50 + 50 showed a significant increase in plant height with no differences among them. Other treatments produced no significantly positive effect on plant height (Table 2). In 2016, all N treatments increased the plant height, but a significant difference was found only between N50 + 150 and the control N0 (Table 2). In most cases, our results did still agree with Ma et al. (2015) that the tallest plants were found in plots that received 150 to 200 kg N ha^{-1}, although only the effect of N treatments on the early growth of canola was investigated in the present study.

Although the plants were taller in most preplant treatments than those in the split application at the same total N-rate, a significant difference was observed only in 2015 between N200 and N50 + 150 (Table 2). These results differ from the findings of Ma et al. (2015) that plants receiving preplant N were significantly taller than plants that received equivalent amounts of side-dressed N for most sites. The difference could be attributed to the weather conditions, especially total rainfall and temperature conditions. Dry soil conditions could hinder root development and further reduce water and nutrient uptake (Wen et al. 2021). In 2016, the growing season rainfall was the lowest, lower by 49.9 mm than that in 2014 and 15.6 mm lower than that in 2015. An average temperature of 14.2 °C during the early stages of canola growth in May 2014, was lower by 1.6 °C and 3.0 °C than that in the same period in 2015 and 2016. These unfavourable weather conditions may have affected the responses of canola plant height to N fertilizer before flowering. In addition, it should be pointed out that plant heights in this study were measured at the early growth stage, and the samples were collected shortly after the application of side-dressed N, which was not expected to have a large effect on plant height. In the literature, plant heights were measured at full flowering or maturity and refer to the final height.

In spite of a few exceptions, either N150 or N200 treatment resulted in the highest biomass (fresh weight and dry weight) and increased the plant height; and no significant differences were found between them. Based on the environmental and economic concerns, a total N-rate of 150 kg ha^{-1} was recommended as the optimum rate. The preplant-only (N150) and preplant in combination with side-dressed (N50 + 100) had a similar effect on canola fresh weight and plant height, with the exception of fresh weight in 2014; however, the former significantly increased dry weight in comparison with the latter (Table 2).

Seed yield is the net resultant of various agronomic inputs influencing growth and yield attributing characters during the life cycle of the crop (Singh et al. 2019). In our study, the yield data have initially been used for machine learning-based canola yield prediction (Wen et al. 2021). From the data, the yield responses to N fertilization were found to be highly dependent on the growing environment, and there were significant differences among the years. On average, seed yield increased significantly with increasing rates of N applications (preplant and side-dressed N applications) in all 3 yr. The highest seed yield was observed with N50 + 100 treatment in 2014, and the treatment showed a comparable

Table 2. Effects of nitrogen (N) treatments on seedling emergence, plant height, fresh weight, dry weight, and seed yield of canola and on disease severity of *Sclerotinia* stem rot (SSR) in Ottawa, Ontario, in 2014, 2015, and 2016.

N treatment	Emergence (%)	Plant height (cm)	Fresh weight (g/plant)	Dry weight (g/plant)	Seed yield* (kg ha^{-1})	SSR (%)
2014						
N0	75.3abc†	31.3b	22.7d	1.6c	2856c	6.4d
N50	82.3ab	34.8ab	31.7bc	1.8bc	3424b	11.0bcd
N100	77.3abc	34.9ab	29.9bcd	2.2abc	3569ab	12.2abc
N150	72.0bc	36.1a	36.1ab	2.7a	3560ab	8.8cd
N200	69.5c	35.9a	40.1a	2.4ab	3508b	17.1a
N50 + 50	78.9abc	36.4a	28.9bcd	2.3abc	3366b	12.5abc
N50 + 100	75.9abc	34.1ab	26.6cd	2.0abc	3901a	10.9bcd
N50 + 150	84.8a	34.0ab	25.5cd	2.2abc	3704ab	15.2ab
2015						
N0	60.9a	38.1d	29.7d	3.1c	2254e	4.8b
N50	58.1a	44.5bcd	42.0c	4.3abc	2973d	7.1a
N100	59.4a	49.9ab	47.6bc	4.4abc	3535bc	7.3a
N150	49.1ab	48.0abc	53.9ab	5.7ab	3489c	2.6cd
N200	35.9b	52.9a	68.6a	6.8a	3733ab	2.4d
N50 + 50	55.0a	47.3abc	49.7bc	4.7abc	3632bc	5.0b
N50 + 100	53.1a	46.0abc	44.0bc	4.1bc	3751ab	4.0bc
N50 + 150	58.8a	41.3cd	44.3bc	3.8bc	3908a	2.0d
2016						
N0	76.9a	35.1b	14.7d	1.9d	1438e	1.8bc
N50	77.9a	38.6ab	18.7c	2.5c	2271d	1.3cd
N100	68.7abc	36.5b	22.4bc	2.9bc	2529c	2.4ab
N150	63.2c	40.8ab	23.6ab	3.0ab	2755bc	0.8de
N200	66.1bc	36.9ab	27.0a	3.3a	2990a	0.8de
N50 + 50	73.1ab	40.0ab	20.5bc	2.6c	2585c	2.9a
N50 + 100	74.9ab	38.1ab	20.4bc	2.4c	2923ab	0.5e
N50 + 150	75.3ab	42.6a	19.8c	2.6c	2826ab	0.4e
3-yr average						
N0	71.0a	34.8b	22.4d	2.2d	2190e	4.3c
N50	72.8a	39.3a	30.8c	2.9cd	2910d	6.5ab
N100	68.5ab	40.4a	33.3c	3.1bc	3203abc	7.3a
N150	61.4bc	41.6a	37.8b	3.8ab	3224abc	4.1c
N200	57.2c	41.9a	45.2a	4.2a	3358a	6.7ab
N50 + 50	69.0a	41.2a	33.0c	3.2bc	3088c	6.8ab
N50 + 100	68.0ab	39.4a	30.3c	2.9cd	3256ab	5.1bc
N50 + 150	72.9a	39.3a	29.9c	2.8cd	3115bc	5.9abc
2014	77.0a	34.7c	30.2b	2.1b	3180b	11.8a
2015	53.8c	46.0a	47.4a	4.6a	3410a	4.4b
2016	72.0b	38.6b	20.9c	2.6b	2540c	1.3c
5440	61.8b	37.8b	34.1a	3.3a	3122a	6.0a
L140P	73.3a	41.6a	31.6b	2.9a	2964b	5.6a

*The data was originally included in a large data set in a machine learning model to estimate site-specific N recommendations (Wen et al. 2021). The canola plants were combine-harvested in early August. Seed yield was determined by combining a 6-row area in each plot and reported on a 100 kg^{-1} moisture basis. The canola hybrid Invigor 5440 and InVigor L150 were tested in 2014; hybrid Invigor L150 was replaced with L140P in 2015 and 2016.

†Means within a column with the same letter within each parameter are not significantly different at $P < 0.05$ (LSD). The samples for the assessment of plant height, fresh weight, and dry weight were taken shortly after the 6th fully expanded leaf stage.

improvement effect with N50 + 150, N100 and N150. Similarly, N50 + 150 treatment had the highest seed yield in 2015, and the treatment showed a comparable improvement effect with N200 and N50 + 100; N200 had the highest seed yield, but it did not significantly differ from those of N50 + 100 and N50 + 150 in 2016 (Table 2).

In all 3 yr, the highest canola yields resulted from the application of N rate 150 and 200 kg N ha^{-1}. At the two N levels, the split-N fertilization strategy promoted canola productivity in most cases, compared with preplant-only application of the equivalent amount. At the 150 kg N ha^{-1} rate, only in 2015, there was a statistical difference in the yield response to the N application methods where the split-N application strategy had higher seed yield than preplant application (Table 2). Considering the crop N uptake and better N economy of canola production, it was recommended to use a combination of 50 kg N ha^{-1} applied at preplant plus 100 kg N ha^{-1} as side-dressed for the optimum seed yield production. Previous studies also showed that the highest seed yield was observed with N50 + 100 treatment (Ma et al. 2015; Ma and Herath 2016), and side-dressed N strategy is more efficient than a preplant-only application with savings of 10–20 kg N ha^{-1} to achieve similar canola seed yield (Ma et al. 2015).

We noted that treatment N50 + 100 did produce the highest canola yields, while N150 could obviously promote plant vegetative growth in some cases. This was because canola plants were more sensitive to preplant N in the early vegetative growth stage and side-dressed N might have been more available for reproductive growth (Ma et al. 2015).

Regardless of treatments, there was a significant difference ($P < 0.05$) in seed yields among 2014, 2015, and 2016. Canola crops are grown in complex environments and even a slight variation in one growing condition could highly impact plant growth. Under unfavorable growing conditions, the surrounding circumstances may develop into the determinants limiting canola production (Wu et al. 2018; Wu and Ma 2018). Heat stress and precipitation distribution were identified as of critical importance in total yield variation (Wen et al. 2021). In 2016, moderate heat stress occurred and the rainfall was much lower than that in 2014 and 2015 (Fig. 1). The unfavorable weather condition served as an explanation of the lowest seed yield in 2016.

The emergence of crops is critical for good stand establishment (Singh et al. 2019). In our study, N fertilizer showed a significantly negative impact on canola emergence. A consistent reduction of emergence was observed with an increase of N-rate in preplant application, and there were significant differences between both treatment N150 and N200 and control N0 (Table 2). The results are in agreement with the findings on a Black Chernozem soil by Kutcher et al. (2005) and on Dark Brown loam and Black clay Chernozemic soils in Saskatchewan by Brandt et al. (2007). The phenomenon is likely caused by the fact that the canola is more sensitive to ammonia and salt injury (Bushong et al. 2018), resulting in a delayed or reduced emergence at the high N fertilizer rates. All the treatments of preplant in combination with side-dressed, including N50 + 100 had no effect on canola emergence in the present study (Table 2), providing indirect evidence that the application of 50 kg N ha^{-1} had no impact on canola emergence. A study carried out in north-eastern Saskatchewan showed that the side banding of 40, 80, and 120 kg N ha^{-1} and seed row placement of 40 kg N ha^{-1} at seeding had no detrimental effect on emergence, while seed row placement of 80 and 120 kg N ha^{-1} generally reduced emergence compared with side banding (Malhi and Gill 2004).

Agronomic practices, especially fertilization, have been shown to affect the development of diseases in many crops. In the study, when the total N-rate was 150 or 200 kg ha^{-1}, N application had a decreasing effect or no effect on SSR incidence, except the N200 and N50 + 150 in 2014; N-rate $\leq$ 100 kg N ha^{-1} showed increasing effect or no effect on it (Table 2). Usually, plants with an optimal nutritional status generally have the highest level of resistance to diseases, and the susceptibility increases as nutritional status deviates from this optimum (Huber et al. 2012). According to the previous analysis, better growth parameters and higher seed yield of canola have been performed at a total N-rate of 150 or 200 kg ha^{-1}. These results might imply that the N supply at a higher rate could help canola to obtain an optimal nutritional status and enhance the resistance to the pathogen causing SSR by altering growth and tissue composition (e.g., the concentration of soluble compounds or defence compounds) (Huber et al. 2012).

The impact of N fertilizer on SSR was different among the 3 yr. In 2015 and 2016, all the high N treatments including N150, N200, N50 + 100, and N50 + 150, significantly reduced SSR incidence with no significant difference among these treatments, with the only exception of N50 + 100 in 2015 (Table 2). In 2014, N150 and N50 + 100 showed no significant effect on SSR incidence in comparison with the control N0, while N200 and N50 + 150 significantly increased the disease incidence (Table 2). In Saskatchewan, Kutcher et al. (2005) also found that the changes in N-rates did not show consistent effects: the high N fertility increased SSR in 1999 and 2000, but the reverse was detected in 2001, and the reason had been attributed to the differences in environmental conditions in those years. It is reported that the general effect of N on the disease susceptibility of plants may be modified by additional factors such as the plant species and plant growth conditions. Under field conditions, fertilizers affect the performance of plants and their parasites directly via their effects on plant nutrition and indirectly by changing the biotic and abiotic environment, which affects pathogen survival and function (Huber et al. 2012). In the present study, the plant height of all N treatments in 2014 was lower than that in the other 2 yr in most cases. Meanwhile, the growing season rainfall in 2014 was much higher than that in the other 2 yr (Fig. 1). Both conditions can lead to the increase of humidity within a crop, which produces a microenvironment more favorable to the development of canola SSR disease. Therefore, the differences in SSR response to equivalent amounts of N, especially to high N-rate, could be attributed to the formation of microenvironment to some extent. The phenomena also indicated that the SSR development was governed more by the climate conditions than the N nutritional status of canola. Nevertheless, of all the N application rates used in this study, only the total N-rate 150 kg ha^{-1} application reduced or had no effect on the SSR incidence, compared with the control N0 in all 3 yr. The results suggested that the 150 kg ha^{-1} was a feasible N supply strategy for canola, taking the development of SSR into consideration. At this N-rate, no significant difference was observed between the preplant-only and split applications in SSR incidence (Table 2).

The SSR incidence was the highest in 2014 and the lowest in 2016, and there were statistical differences among these years (Table 2). The differences in disease pressure are likely due to the weather and environmental conditions required for the disease development. The *S. sclerotiorum* infection of canola most commonly occurs through carpogenic germination, which is characterised by the release of thousands of ascospores from apothecia (Lane et al. 2019). Soil moisture is the main factor controlling carpogenic germination of sclerotia. The high levels of precipitation can exacerbate the disease caused by *S. sclerotiorum*, by aiding in the establishment of *S. sclerotiorum* in planta (Koch et al. 2007). The drier environments resulted in a reduction in the number or elimination of apothecia (Ferraz et al. 1999), and then the chance of infection by the pathogen was greatly reduced. A comparison of the growing seasons (May, June, July, and August) of the 3 yr shows that the monthly precipitation was the highest in 2014 and the lowest in 2016 (except July); and except June, the monthly average temperature was lowest in 2014 and the highest in 2016 (Fig. 1). Based on the above analysis, the weather conditions were more favourable for SSR infection and disease development in 2014 and less for the same period in 2015 and 2016. Therefore, inoculum levels could have been higher in 2014, resulting into differential disease responses in 2014 relative to other years. As a result, more severe SSR developed in 2014 than in 2015 and 2016 (Table 2).

Studies have demonstrated that the application of fertilizers in different amounts and forms has effects on microbial activity in the soil and rhizosphere, as well as the presence of soil-borne pathogens (Aira et al. 2010; Huber et al. 2012). There was a tendency for high N to substantially increase the proportion of pathogenic genera in sugarcane rhizosphere and soil, which indicates that increasing N fertilizer modifies the composition of the fungal communities and has a negative impact on plant health by promoting pathogenic fungi (Paungfoo-Lonhienne et al. 2015). The decrease in common root rot disease levels of spring wheat at low N fertility appeared to be associated with lower levels of *Fusarium* spp., particularly *F. pseudograminearum* (Fernandez and Zentner 2005). However, it is still unknown whether and how N fertilizer rates will modify the fungal communities in the canola rhizosphere and eventually affect the severities of SSR in canola.

The changes in the relative abundance of the fungal population in response to N doses are not restricted to the pathogen but span a wide range of microorganisms taxa, including genera known to influence plant health. It is a promising strategy to reduce disease incidence and improve crop performance by manipulating the microbial community in the rhizosphere based on reasonable use of agrochemicals (Paungfoo-Lonhienne et al. 2015). It is possible that the impact of N-fertilizer application rates not only on the SSR (*S. sclerotiorum*) in canola rhizosphere and soil but also on rhizosphere microorganism communities.

The variety of the crop is another factor that affects the N action on disease severity. Susceptible cultivars are at a higher risk for diseases than the more resistant cultivars when N fertilizer application exceeds the optimal rate (Long 2000). In our study, no significant differences were observed between InVigor L140P and InVigor 5440 in response to SSR; however, this phenomenon does not imply that the effect of variety susceptibility on the disease can be ignored in future practices, as this study only tested two varieties. To determine if canola variety responds differently to N treatments in regard to the SSR, *B. napus* cultivars with different disease-resistant levels should be chosen for further study.

The different seed yield in responses to N treatments between varieties InVigor L140P (InVigor L150 in 2014) and InVigor 5440 were observed among 3 yr. For InVigor 5440, N50 + 100 treatments showed the highest yields in 2014, and no significant differences were found with N100, N150, and N50 + 150. In 2015, N50 + 100 showed the highest yields, and no significant differences presented with N100, N200, and N50 + 150. In 2016, N200 had the highest yields, and no differences were observed with N150, N50 + 100, and N50 + 150. For InVigor L140P, N50 + 150 showed the highest yield in 2015, and no significant differences were observed with N150, N200, N50 + 50 and N50 + 100; N50 + 100, in 2016, had no difference with N150 and N200. For InVigor L150, N50, N100, and N150 showed the highest yields in 2014, and they are comparable (Table 3).

The varieties also showed different growth responses to N treatments. The emergence of InVigor L140P was higher than that of InVigor 5440, but the fresh weight was lower (Table 2). For InVigor 5440, the plant height was significantly increased by both N150 and N200 in 2014, by N200 in 2015, and by N50 + 150 in 2016. For InVigor L140P, there was no significant effect in 2014 and 2016; N100, N150, N200 and N50 + 50 application significantly increased the plant height in 2015, with no

Table 3. Effects of nitrogen (N) treatments on plant height shortly after the 6th fully expanded leaf stage and seed yield in two different canola varieties in Ottawa, Ontario, in 2014, 2015 and 2016.

		Plant height (cm)		Seed yield* (kg ha^{-1})	
Year	N treatment	InVigor 5440	InVigor L140P	InVigor 5440	InVigor L140P†
2014	N0	29.5b‡	33.0a	2856c	2903c
	N50	34.5ab	35.0a	3424b	3548a
	N100	34.8ab	35.0a	3569ab	3517ab
	N150	37.0a	35.3a	3560ab	3295ab
	N200	37.3a	34.5a	3508b	3195bc
	N50 + 50	34.3ab	38.5a	3366b	2728c
	N50 + 100	33.8ab	34.5a	3901a	2289d
	N50 + 150	31.0b	37.0a	3704ab	1521e
2015	N0	39.3b	37.0e	2248e	2261d
	N50	42.3ab	46.8bcde	2813d	3133c
	N100	42.3ab	57.5a	3665ab	3405bc
	N150	45.3ab	50.8abcd	3235c	3744a
	N200	51.0a	54.8ab	3617ab	3849a
	N50 +50	41.8b	52.8abc	3414bc	3851a
	N50 + 100	48.5ab	43.5cde	3801a	3702ab
	N50 + 150	41.8ab	40.8de	3800a	4015a
2016	N0	30.8b	39.5a	1373d	1503e
	N50	37.3ab	40.0a	2412c	2131d
	N100	34.8ab	38.3a	2588bc	2471c
	N150	35.8ab	45.8a	2702abc	2809ab
	N200	34.3ab	39.5a	3041a	2939ab
	N50 + 50	36.5ab	43.5a	2550bc	2620bc
	N50 + 100	32.3b	44.0a	2782ab	3064a
	N50 + 150	42.8a	42.5a	3003a	2649bc

*This data was originally included in a large data set in a machine learning model to estimate site-specific N recommendations (Wen et al. 2021).

†For the yield, the canola hybrid Invigor 5440 and InVigor L150 were tested in 2014; then hybrid Invigor L150 was replaced with L140P in 2015 and 2016.

‡Means within a column by the same letter within each parameter are not significantly different at $P < 0.05$ (LSD).

significant differences in plant height being found among these N treatments (Table 3). The plant responses were likely a result of the interaction among various factors such as crop, weather, and rates and timing of N-fertilizer application.

The use of precision agriculture technology to guide crop input application may make crop production environmentally friendly and cost-effective by optimizing input use efficiency and avoiding interactions that would decrease crop yield (Wallace 1994). Successful application of precision agriculture technology requires information on crop response to many factors including fertilization, yields, and disease management. The N-rate where high nutrition is supplied to stimulate crop growth but decrease disease incidence can be considered ideal because it brings both optimal growth and seed yield and a greater level of resistance to diseases. In the present study, the fertilizer management of a total of 150 kg N ha^{-1} as preplant in combination with the side-dressed application (N50 + 100), could ensure optimum growth and seed yields, and avoid severe development of SSR. Meanwhile, it did not result in a decrease in plant emergence. The appropriate N rate and management strategies found in this study are in line with recommendations derived from multi-site-year experiments in eastern Canada (Ma et al. 2019, 2020). However, differences in N fertility form and rate, management practices, and environmental conditions, as well as the interaction among these factors, can all influence plant yield and quality and the development of SSR. In the present study, the lower disease pressure for SSR, except in 2014, may have not sufficiently demonstrated the N effect on SSR, which would make the experimental results deviate from the actual situation to some extent. In addition, samples were taken shortly after the side-dressing application, and the side-dressed N might not have fully affected plant growth parameters. Therefore, further studies with adequate disease levels and longer intervals between fertilizer application and sample date are needed to verify the conclusions and continuously optimize the fertilizer management strategy to benefit future canola production.

Conclusions

Our results indicated that the total economical rate 150 kg N ha^{-1}, applied as preplant or as the split with side-dress (N50 + 100) applied at the 6-leaf stage, was beneficial not only in promoting the canola vegetative growth (plant height, fresh weight, and dry weight) and seed yield but also in minimizing the negative impact of SSR disease. Although the N treatment 150 kg ha^{-1} as preplant-only (N150) was more available to vegetative growth than split application (N50 + 100) in some cases, the highest seed yield of canola produced at N50 + 100. Meanwhile, the treatment N50 + 100 did not decrease the emergence of canola. Therefore, we recommend the split-N fertilizer strategy of 50 kg ha^{-1} at preplant plus 100 kg ha^{-1} as a side-dress at the 6-leaf stage, as a "balanced" nutrient supply.

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Competing interests statement

The authors declare that there is no conflict of interest regarding the publication of the manuscript.

Contributors' statement

BM and AX designed the study; BM, AX, YC and SL performed the research; and FG, BM and AX drafted the manuscript. All coauthors read, revised, approved the final version of the manuscript submitted, and agreed to be accountable for all aspects of the work.

Data availability statement

There is no additional data.

References

Aira, M., Gómez-Brandón, M., Lazcano, C., Bååth, E., and Domínguez, J. 2010. Plant genotype strongly modifies the structure and growth of maize rhizosphere microbial communities. Soil Biol. Biochem. **42**: 2276–2281.

Brandt, S.A., Malhi, S.S., Ulrich, D., Lafond, G.P., Kutcher, H.R., and Johnston, A.M. 2007. Seeding rate, fertilizer level and disease management effects on hybrid versus open pollinated canola (*Brassica napus* L.). Can. J. Plant Sci. **87**: 255–266.

Bushong, J., Lofton, J., Sanders, H., and Stamm, M. 2018. Great plains canola production handbook. Kansas State University in cooperation with Oklahoma State University, the University of Nebraska-Lincoln, Texas A&M, Great Plains Canola Association, and U.S. Canola Association. p. 16.

Derbyshire, M.C., and Denton-Gile, M. 2016. The control of sclerotinia stem rot on oilseed rape (*Brassica napus*): current practices and future opportunities. Plant Pathol. **65**: 859–877.

Fernandez, M.R., and Zentner, R.P. 2005. The impact of crop rotation and N fertilizer on common root rot of spring wheat in the Brown soil zone of western Canada. Can. J. Plant Sci. **85**: 569–575.

Ferraz, L.C.L., Café Filho, A.C., Nasser, L.C.B., and Azevedo, J. 1999. Effects of soil moisture, organic matter and grass mulching on the carpogenic germination of sclerotia and infection of bean by *Sclerotinia sclerotiorum*. Plant Pathol. **48**: 77–82.

Hoffland, E., Jeger, M.J., and Van Beusichem, M.L. 2000. Effect of nitrogen supply rate on disease resistance in tomato depends on the pathogen. Plant Soil, **218**: 239–247.

Hoffland, E., Van Beusichem, M.L., and Jeger, M.J. 1999. Nitrogen availability and susceptibility of tomato leaves to *Botrytis cinereal*. Plant Soil, **210**: 263–272.

Huber, D., Römheld, V., and Weinmann, M. 2012. Relationship between nutrition, plant diseases and pests. Marschner's Mineral Nutrition of Higher Plants. Academic Press, USA. doi:10.1016/B978-0-12-384905-2.00010-8.283-298.

Koch, S., Dunker, S., Kleinhenz, B., Rohrig, M., and Von Tiedemann, A. 2007. A Crop loss-related forecasting model for *Sclerotinia* stem rot in winter oilseed rape. Phytopathology, **97**: 1186–1194.

Kutcher, H.R., Malhi, S.S., and Gill, K.S. 2005. Topography and management of nitrogen and fungicide affects diseases and productivity of canola. Agron J. **97**: 533–541.

Lane, D., Denton-Giles, M., Derbyshire, M., and Kamphuis, L.G. 2019. Abiotic conditions governing the myceliogenic germination of *Sclerotinia sclerotiorum* allowing the basal infection of *Brassica napus*. Australas. Plant Path. **48**: 85–91.

Li, Y.S., Yu, C.B., Liao, X., Hu, X.J., Xie, L.H., Zhang, S.J., et al. 2013. Influence analysis of application of NPK fertilizer on epidemics of rapeseed *Sclerotinia* stem rot. Chin. J. Oil Crop Sci. **35**: 290–294.

Liu, X.N., Liu, H.K., Huang, Y.F., and Ye, Y.L. 2015. Relationships between nitrogen application rate soil nitrate-nitrogen, plant nitrogen concentration and wheat scab. J. Plant Nutr. Ferti. **21**: 306–317.

Long, D.H. 2000. Effect of nitrogen fertilization on disease progress of rice blast on susceptible and resistant cultivars. Plant Dis. **84**: 403–409.

Ma, B.L., Biswas, D.K., Herath, A.W., Whalen, J.K., Ruan, S.Q., Caldwell, C., et al. 2015. Growth, yield, and yield components of canola as affected by nitrogen, sulfur and boron application. J. Plant Nutr. Soil Sci. **178**: 658–670.

Ma, B.L., and Herath, A.W. 2016. Timing and rates of nitrogen fertilizer application on seed yield, quality and nitrogen-use efficiency of canola. Crop Pasture Sci. **67**: 167–180.

Ma, B.L., and Wu, W. 2016. Crop productivity and environment impact in a maize-legume rotation system: A review. Pages 1–13 in Crop Rotations: Farming Practices, Monitoring and Environmental Benefits. B.L. Ma, ed. Nova Science Publisher, Inc. New York, N.Y.

Ma, B.L., Zhao, H., Zheng, Z.M., Caldwell, C., Mills, A., Earl, H., et al. 2016. Optimizing seeding dates and rates for canola production in the humid eastern Canadian agroecosystems. Agron. J. **108**: 1869–1879.

Ma, B.L., Zheng, Z.M., de Silva, A., Whalen, J.K., Pageau, D., Vanasse, A., et al. 2020. Graphical analysis of nitrogen and sulfur supply on yield and related traits of canola in eastern Canada. Nutr. Cycl. Agroecosys. **118**: 293–309.

Ma, B.L., Zheng, Z.M., Whalen, J.K., Caldwell, C., Vanasse, A., Pageau, D., et al. 2019. Uptake and nutrient balance of nitrogen, sulfur, and boron for optimal canola production in eastern Canada. J. Plant Nutr. Soil Sci. **182**: 252–264.

MacNish, G.C. 1985. Methods of reducing *Rhizoctonia* patch of cereals in Western Australia. Plant Pathol. **34**: 175–181.

Malhi, S.S., and Gill, K.S. 2004. Placement, rate and source of N, seed row opener and seeding depth effects on canola production. Can. J. Plant Sci. **84**: 719–729.

Paungfoo-Lonhienne, C., Yeoh, Y.K., Kasinadhuni, N.R.P., Lonhienne, T.G.A., Robinson, N., Hugenholtz, P., et al. 2015. Nitrogen fertilizer dose alters fungal communities in sugarcane soil and rhizosphere. Sci. Rep. **5**: 8678.

Pumphrey, F.V., Wilkins, D.E., Hane, D.C., and Smiley, R.W. 1987. Influence of tillage and nitrogen fertilizer on *Rhizoctonia* root rot (bare patch) of winter wheat. Plant Dis. **71**: 125–127.

Sharma, P., Meena, P.D., Verma, P.R., Saharan, G.S., Mehta, N., Singh, D., and Kumar, A. 2015. *Sclerotinia sclerotiorum* (Lib.) de Bary causing *Sclerotinia* rot in oilseed *Brassicas*: A review. J. Oilseed Brassica. **6**(Special): 1–44.

Singh, R., La, M., Singh, G., and Kumar, T. 2019. Effect of nitrogen and phosphorus on growth parameter and yield of canola (*Brassica napus* L.). J. Pharmacogn Phytochem. **8**: 380–384.

Smiley, R.W., Collins, H.P., and Rasmussen, P.E. 1996. Diseases of wheat in long-term agronomic experiments at Pendleton, Oregon. Plant Dis. **80**: 813–820.

Talukder, Z.I., McDonald, A.J.S., and Price, A.H. 2005. Loci controlling partial resistance to rice blast do not show marked QTL environment interaction when plant nitrogen status alters disease severity. New Phytol. **168**: 455–464.

Wallace, A. 1994. High-precision agriculture is an excellent tool for conservation of natural resources. Commun. Soil Sci. Plant Anal. **25**: 45–49.

Wen, G.Q., Ma, B.L., Vanasse, A., Caldwell, C.D., Earl, H.J., and Smith, D.L. 2021. Machine learning-based canola yield prediction for site-specific nitrogen recommendations. Nutr. Cycl. Agroecosyst. **121**: 241–256.

Wu, W., Ma, B.L., and Whalen, J.K. 2018. Enhancing rapeseed tolerance to heat and drought stresses in a changing climate: perspectives for stress adaptation from root system architecture. Pages 87–157 in Advances in Agronomy. Vol. 151. D.L. Sparks, ed. Academic Press. doi:10.1016/ bs.agron.2018. 05.002.

Wu, W., and Ma, B.L. 2018. Assessment of canola crop lodging under elevated temperatures for adaptation to climate change. Agric. For Meteorol. **248**: 329–338. doi:10.1016/ j.agrformet.2017.09. 017.