Growth, yield, and yield components of canola as affected by nitrogen, sulfur, and boron application

Bao-Luo Ma[1]*, Dilip K. Biswas[1], Aruna W. Herath[1], Joann K. Whalen[2], S. Qianying Ruan[2], Claude Caldwell[3], Hugh Earl[4], Anne Vanasse[5], Peter Scott[6], and **Donald L. Smith[2]**

[1] Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre, Ottawa, ON K1A 0C6, Canada
[2] McGill University, 21,111 St. Anne-de-Bellevue, QC H9X 3V9, Canada
[3] Dalhousie University, Truro, NS B2N 5E3, Canada
[4] University of Guelph, Guelph, ON N1G 2W1, Canada
[5] Laval University, Laval, QC G1V 0A6, Canada
[6] New Brunswick Department of Agriculture, Aquaculture and Fisheries, Fredericton, NB E3B 5H1, Canada

Abstract

Developing efficient nutrient management regimes is a prerequisite for promoting canola (*Brassica napus* L.) as a viable cash crop in eastern Canada. Field experiments were conducted to investigate the growth, yield, and yield components of canola in response to various combinations of preplant and sidedress nitrogen (N) with soil-applied sulfur (S) and soil and foliar-applied boron (B). Canola yield and all its yield components were strongly correlated (r^2 = 0.99) with the amount of N applied, as was the above-ground biomass at 20% flowering and the leaf area index. Sidedress N was more efficiently utilized by the crop, leading to greater yields than preplant N application. On average, canola yields increased by 9.7 kg ha^{-1} for preplant N application and by 13.7 kg ha^{-1} for sidedress N application, for every kg N ha^{-1} applied, in 6 of the 10 site-years. Soil-applied S also increased canola yields by 3–31% in 7 of the 10 site-years, but had no effect on yield components. While there was no change in yield from soil-applied B, the foliar B application at early flowering increased yields up to 10%, indicating that canola plants absorb B efficiently through their leaves. In summary, canola yields were improved by fertilization with N (8 of 10 site-years), S (7 of 10 site-years) and B (4 of 10 site-years). Yield gains were also noted with split N-fertilizer application that involved sidedressing N between the rosette and early flowering stage. Following these fertilizer practices could improve the yield and quality of canola crop grown in rainfed humid regions similar to those in eastern Canada.

Key words: *Brassica napus* / fertilizer application / nutrient management / yield components

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1 Introduction

Brassica napus L., known as Argentine rapeseed, is a high-value crop for both edible oil and animal meal protein. Canola is a crop bred from rapeseed to contain low erucic acid (a known health concern) in the oil and low glucosinolate (an anti-nutritive factor) concentrations in its byproduct oilmeal (*Potts* et al., 2003). Therefore, canola is generally referred to as "Double Zero Rapeseed" and consumption of canola is beneficial to humans and livestock. Moreover, properties of the oilseed such as its low saturated fat concentration and 10% oxygen by weight favor its efficient combustion under cold conditions, making canola a desirable and renewable feedstock for biodiesel production (*Blackshaw* et al., 2011).

Under favorable environmental conditions, canola has the highest seed-yield potential among the Brassicaceae crops (*Kimber* and *McGregor*, 1995). Thus, canola has been rapidly adopted and has become a major cash crop in western Canada. Canola production is far less common in eastern Canada. One of the main reasons for its tardy adoption is the lack of crushing facilities within a reasonable distance from major growing areas of eastern Canada, which made it economically unattractive to farmers in this region. Consequently, there was little research to facilitate adapting the crop to growth conditions and environment of eastern Canada. However, recent operationalization of a canola and soybean crushing plant and oil refinery in Becancour, Quebec by Twin River Technologies–Enterprise De Transformation de Graines Oléagineuses (TRT-ETGO) significantly brightened the prospects of canola production in eastern Canada (*Better Farming*, 2011). Between 2006 and 2011, canola production in eastern Canada increased by 305% over 57,000 hectares, increasing farmgate cash receipts by almost 700% to $46.3 million (Francis Rory, President of the Eastern Canada Oilseed Research Alliance, Inc.; pers. comm.). There is an urgent need for developing sound agronomic practices for canola production in eastern Canada, particularly with respect to N fertilizer application and improved N-use efficiency (NUE), for the environmental and economic sustainability of canola production.

* Correspondence: Dr. B. L. Ma; e-mail: baoluo.ma@agr.gc.ca

Generally, canola requires more nutrients than small-grain cereals (*Rathke* et al., 2005). Adequate N fertilization is vital because it increases yield by promoting more vigorous growth and development as reflected by increasing plant height, leaf area development and overall crop assimilation (*Wright* et al., 1988). Besides, several studies conducted in western Canada showed that N fertilizer increases canola yield by influencing key yield components such as branches per plant, pods per plant, number of seeds per pod and seed weight (*Gan* et al., 2007; *Malhi* et al., 2013). Since N is vulnerable to loss from the soil, particularly in humid temperate zones such as eastern Canada where leaching and denitrification occur during the growth season (*Ma* et al., 2010a, 2010b), N availability could be the limiting factor for canola growth and yield. A sufficient and timely supply of N fertilizer is required to optimize seed yield. In addition, sulfur (S) is an essential component of certain plant amino acids and proteins (*Subedi* and *Ma*, 2009), and canola yield was often enhanced by S fertilization in western Canada (*Malhi* and *Gill*, 2007). Boron (B), a micronutrient, is also a key element in carbon metabolism, sugar transport and flower pollination (*Subedi* and *Ma*, 2009). Both S and B are important nutrients required for canola to enhance canola development, hence deficiencies of S, and B could restrict canola yield significantly (*Malhi* and *Gill*, 2007). Hidden hunger for (micro) nutrients could be one of the contributing factors of low N-use efficiency (*Subedi* and *Ma*, 2009; *Gao* and *Ma*, 2015). Therefore, effective fertilizer management strategies are a prerequisite to ensure optimum seed yields and seed quality. Moreover, such fertilizer management strategies must be economically viable and must ensure minimized negative impacts on the environment.

While several fertilization studies with canola were conducted in the semi-arid regions of western Canada on black, brown, and grey chernozemic soils (*Cutforth* et al., 2009; *Gan* et al., 2007; *Harker* et al., 2013; *Malhi* et al., 2013), there was limited research in the humid regions of eastern Canada (*Simard* et al., 2009). Data on N-use efficiency of canola and responses to B and S fertilization in eastern Canada were not available, but were expected to exhibit a wider range of values than in western Canada due to greater site-specific variability in climate, soils and agronomic practices in eastern Canada. We hypothesized that both grain yield and the most economic rate of N (MERN) of canola crops would vary among site-years, and would also vary with the application rate and timing of N, S, and B fertilizers for canola production in rainfed humid regions. Multiple field experiments were therefore established to develop site-specific management practices for growing canola in eastern Canada with the specific objective of determining the optimum rate and timing of N, S, and B fertilizers on canola growth, yield and yield components.

2 Material and methods

Field experiments were conducted in 2011 and 2012 at six locations in Eastern Canada: the Central Experimental Farm, Ottawa, ON (45°23′ N, 75°43′ W); Macdonald Campus of McGill University in Ste. Anne-de-Bellevue, QC (45°25′ N, 73°56′ W); the Potato Research Centre in Fredericton, NB (45°55′ N, 66°36′ W); Lyndhurst Farms Ltd. in Canning, NS (45°01′ N, 64°26′ W); Laval University Research Farm in St-Augustin-de-Desmaures, QC (45°34′ N, 73°41′ W); and Elora Research Station in Elora, ON (43°38′ N, 80°24′ W). Average spring and summer temperature and rainfall for these site-years are presented in Fig. 1. The soil type, preceding crop, and the soil basic physical and chemical properties (0–30 cm depth) are given in Table 1.

2.1 Experimental design and field management

An unbalanced N × S × B factorial experiment was established in various fields each site-year, with < 1 km between fields used in 2011 and 2012 at the same location. In 2011, treatments included six levels of N (0, 50, 100, 150 kg ha^{-1} at preplant and 50 kg ha^{-1} at preplant plus 50, and 100 kg ha^{-1} sidedressed at the six-leaf stage), two levels of S (0 and 20 kg ha^{-1} at preplant) and three levels of B [preplant at the rate of 0 and 2 kg ha^{-1} and 500 g B ha^{-1} foliar-applied at the 20% flowering stage, corresponding to phenological growth stage

Table 1: Soil (0–30 cm) characteristics of field sites before canola planting in 2011 and 2012.

Location	Ottawa		Ste. Anne-de-Bellevue		Fredericton		Canning		Elora	Laval
	2011	2012	2011	2012	2011	2012	2011	2012	2012	2012
Soil type	Sandy loam	Sandy loam	Loam	Sand	Loam	Sandy loam	Sandy loam	Sandy loam	Loam	Sandy loam
Preceding crop	Barley	Soybean	Wheat	Fallow	Forage	Hay	Spring wheat	Winter wheat	Soybean	Wheat
Soil pH	7.1	6.5	5.2	5.0	5.7	5.6	6.0	6.0	7.8	6.1
Organic matter / g kg^{-1}	26.0	40.3	41.0	34.0	53.0	55.0	29.0	34.0	42.0	37.0
Soil available P[a] / mg kg^{-1}	34	114	87	94	175	149	486	444	24	197
Soil available K/ mg kg^{-1}	60	128	103	86	63	146	163	146	57	345

[a]At the Ottawa and Elora sites, available P refers to sodium bicarbonate test P and available K was the ammonium acetate-extractable K. At the other sites, Mehlich-3 extraction was performed to determine P and K fertilizer recommendations.

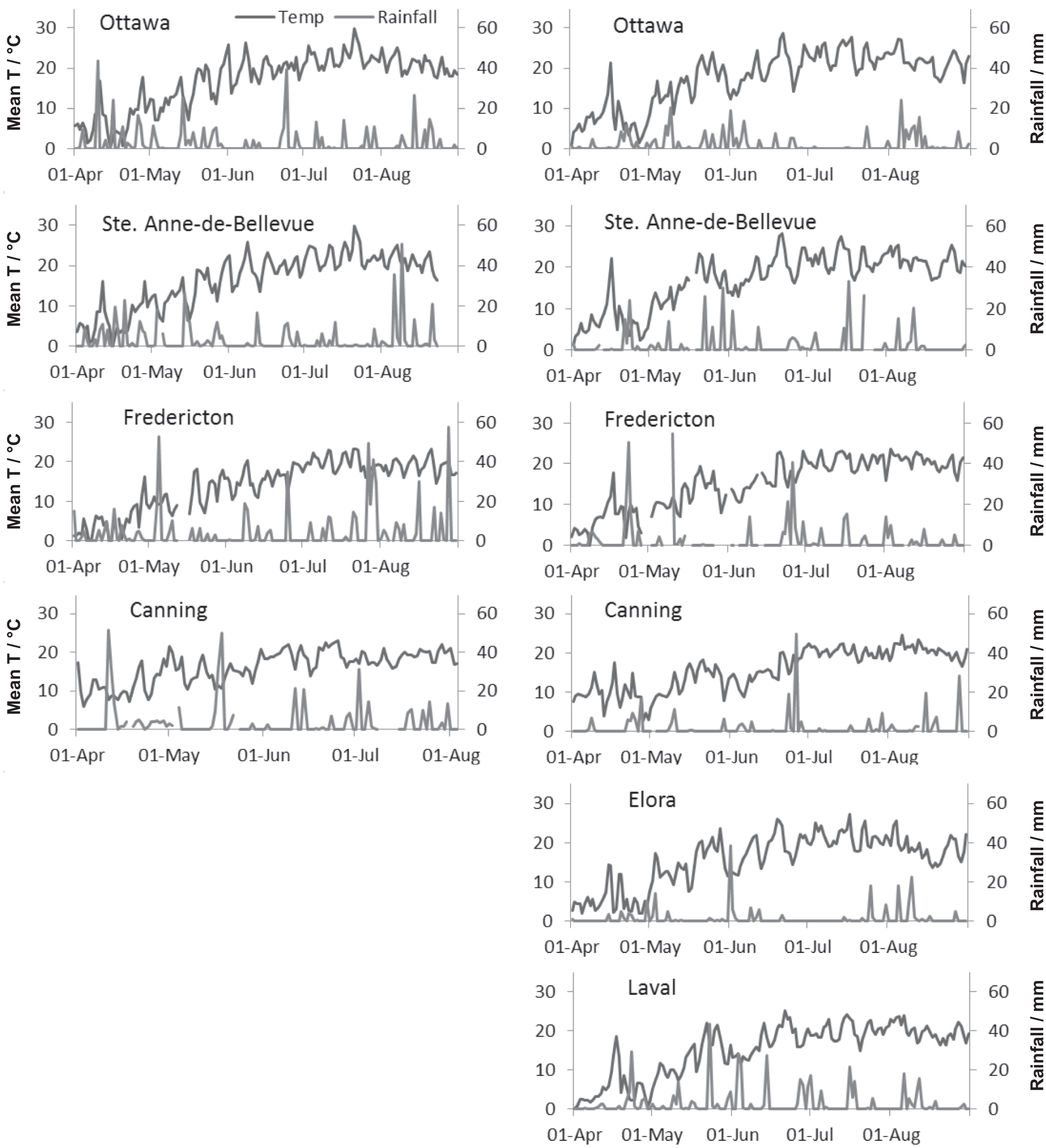

Figure 1: Daily mean air temperature (T) and total rainfall during the growing season in 2011 and 2012 at Ottawa and Elora, Ontario; Fredericton, New Brunswick; Ste. Anne-de-Bellevue and Laval, Quebec; and Canning, Nova Scotia.

(GS) 62]. Sulfur and B were applied only in plots that received 100 kg ha^{-1} or more N, and the combined N, S, and B treatments were tested at all sites except Laval and Elora. In 2012, two additional N treatments of 200 kg ha^{-1} at preplant and 50 kg ha^{-1} at preplant plus 150 kg ha^{-1} sidedressed at the six-leaf stage were included and tested at all six sites. At each site-year, the experiment was arranged in a randomized complete block design with four replications.

Field preparation involved chisel plowing to a depth of about 15–20 cm in the fall, using the DMI Elco Tiger machine, and cultivated to a depth of 10–15 cm in the spring with the C-shank cultivator before broadcasting the preplant N fertilizer (urea, 46-0-0) at the correct application rate for each N treatment plot. Also broadcast in the preplant period were S fertilizer (ammonium sulfate formulated as 21-0-0 with 24% S) and soil-applied B fertilizer (Alpine B, containing 10% boric acid). To balance the N contained in the ammonium sulfate, 17.5 kg N ha^{-1} as urea were applied by hand to all the zero-N control plots prior to planting. In addition, all plots received a broadcast application of P and K at a rate determined from the soil test recommendations for the site (Table 1), to ensure ample P and K for canola production. Within 24 h, the field was cultivated again with an S-tine cultivator to incorporate the preplant fertilizers into soil before seeding canola.

Canola (*Brassica napus* L. hybrid InVigor 5440, LL) was sown at a rate of 5 kg ha^{-1} at a seeding depth of 1–2 cm. The size of the plots varied among sites with row widths ranging from 12.5–17.8 cm and row length of 8–10 m. Weeds were controlled by spraying Liberty herbicide (post emergence) at all sites. The post-emergence fertilization included sidedress N fertilizer application (urea, 46-0-0) applied by hand on the soil surface. The foliar application of B as 500 g B ha^{-1} in 200 L ha^{-1} solution, containing the surfactant Agral 90 at 0.125% (v/v) to enhance the absorption of B through the foliage, was done with a backpack sprayer at 207 kPa (30 psi).

2.2 Sampling and data collection

The weekly record of phenology was based on the Phenological Growth Stage (GS) and BBCH-identification keys of oilseed rape (*Weber* and *Bleiholder*, 1990; *Lancashire* et al., 1991). Plant biomass was determined by collecting plants in a 1 m × 1 row area at the 20% flowering stage (GS 62). At the Ottawa and Laval sites, leaf area index (LAI) was determined at rosette and 20% flowering stages by measuring the plant canopy between two rows of canola.

At physiological maturity, plants were collected from a 1 m × 2 row area of each plot and the number of plants m^{-2} was counted. These plants were dried in a forced-draft oven at 50°C and then weighed and threshed to determine the harvest index (HI). An additional sample of five plants per plot was taken at random from an inner row to determine the yield components: branches $plant^{-1}$, pods $plant^{-1}$, seeds pod^{-1}, and 1000-seed weight. Grain yield and moisture were determined by combining central 4 to 6 rows of canola in each plot and reported on a 100 g kg^{-1} water basis.

At the Ottawa site, the percentage of distinctly green (DGR), brown, tan, and empty seeds (total poor-quality seed) was determined based on a color guide produced by the Ontario Canola Growers Association. According to the Canadian Grain Commission Guidelines (*CGC*, 2014), a canola counting paddle that holds 100 seeds, a roller, and double-sided masking tape was used to crush the seed to better determine the color differences. Two sets of 100-seed samples per plot were used and average values were taken for statistical analysis.

2.3 Data analysis

This was an unbalanced factorial experiment, thus, the data were analyzed in two different ways: (1) general linear model (GLM) procedure of statistical analysis system (SAS) which includes the statistical methods of analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) to estimate partial correlation coefficients, and (2) MIXED procedure of SAS to analyze the sidedress (split) *versus* preplant N application rates using the LSMEANS statement with the print difference (PDIFF) option. A pooled analysis of variance across site-years was also attempted with the common treatments but not reported due to the large heterogeneous error variances, which were likely caused by the unusual drought stress at some sites in 2012. Treatment mean differences were separated according to the protected-$LSD_{0.05}$ test.

2.4 Estimation of maximum economic rate of nitrogen

Assuming that an average canola price was \$ 0.50 kg^{-1} and N fertilizer cost was \$ 1.00 kg^{-1} N, the maximum economic rate of N (MERN) was calculated according to *Rashid* and *Voroney* (2005) for each site-year when there was a yield response to N. It is a single target tare based on the formula of grain yield (Y) response to N rate (X):

$$Y = aX^2 + bX + c, \quad (1)$$

where both *Y* and *X* have the same unit (kg ha^{-1}), and *a, b, c* are the coefficients. Taking the first derivative of this quadratic equation $Y' = 2aX + b$, and setting $Y' = 0$, the N fertilizer rate (X_{max}) to achieve the maximum yield (Y_{max}) is obtained as:

$$X_{max} = -b / 2a. \quad (2)$$

Therefore, by substituting X_{max} into Eq. (1):

$$Y_{max} = (-b^2 / 4a) + c, \quad (3)$$

$$\text{MERN} = (X_{max}\,(2Y_{max} - X_{max} \times \text{B})) / 2\text{Y}_{max}, \quad (4)$$

where X_{max} refers to the N rate at which the largest yield response (*i.e.*, Y_{max}) occurs (*Janovicek* and *Stewart*, 2014) and where *B* = *N* Cost/Grain value = 1/0.5 = 2, *i.e.*, B represents the price ratio of 1 kg of fertilizer N to the price of 1 kg of canola grain (*Rashid* and *Voroney*, 2005).

3 Results and discussion

3.1 Weather

While the 2011 growth season started slightly late in the Maritime Provinces, there was sufficient heat and adequate rainfall for canola crop production across eastern Canada. In contrast, the 2012 growth season occurred at least 2 weeks earlier than normal and canola suffered from medium to severe drought stress between flowering and maturity (Table 2; Fig. 1), especially in the Mixwood regions of eastern Ontario and southern Quebec (43–46°N, 71–79°W). For example, there was only 23 mm of total rainfall at the Ottawa site from 20 June to 5 Aug 2012 and the 45-y long-term total rainfall for the same period was 160 mm (*Ma* et al., 2006).

Table 2: Planting date and occurrence of major phenological growth stages of canola at each site-year.

Location	Ottawa		St. Anne-de-Bellevue		Fredericton		Canning		Elora	Laval
	2011	**2012**	**2011**	**2012**	**2011**	**2012**	**2011**	**2012**	**2012**	**2012**
Planting date	May 11	May 14	May 12	May 7	Jun 3	May 28	May 4	May 17	May 8	May 5
Emergence	May 20	May 20	May 19	May 24	Jun 7	Jun 9	May 9	May 24	May 14	May 18
GS 31 (sidedress N)	Jun 14	Jun 7	Jun 9	Jun 13	Jul 7	Jul 3	Jun 8	Jun 26	Jun 21	Jun 11
20% flowering (GS 62)	Jun 20	Jun 22	Jun 27	Jun 26	Jul 11	Jul 12	Jun 20	Jul 6	Jun 28	Jun 21
Maturity	Aug 2	Aug 8	Aug 17	Aug 6	Sept 12	Sep 2	Aug 18	Aug 18	Aug 1	Aug 6

In comparison, the weather in western Canada is generally drier and more continental (colder winter but hotter summer) than in eastern Canada. Accordingly, soils in western Canada contain generally higher soil organic matter with less N leaching (*Malhi* and *Gill*, 2007) than those in eastern Canada. The prevailing wet and cool soil conditions in early spring and frequent rainfall events and erratic distribution during the growth season in eastern Canada often result in soil N losses through NO_3-N leaching, N_2O emissions and NH_3 volatilization with preplant N fertilization (*Ma* et al., 2006, 2010a, 2010b). Other anionic nutrients that move through mass flow in the soil solution, such as SO_4^{2-}, are susceptible to leaching in this humid environment, particularly in coarse-textured soils (sandy and sandy-loam) that have limited anion exchange capacity.

3.2 Effects of N, S, and B fertilizer applications on canola growth parameters

3.2.1 Leaf area index (LAI)

The ability of a plant to produce biomass depends on the size, efficiency, and longevity of the photosynthetic organs. Figure 2 illustrates the LAI measured at rosette in 2011, and at 20% flowering stage in both years at Ottawa and in 2012 at Laval. In both years, LAI values increased with increasing amounts of preplant N fertilizer between rosette and 20% flowering stages at the Ottawa site. The LAI values were significantly greater in plots receiving preplant 150 kg N ha^{-1} (150N) than plots that received the same amount of total N (50N+100N) with N sidedressed at the rosette stage. However, this difference disappeared at the early flowering stage, indicating that the additional N applied by sidedressing was utilized by the crop. In 2011, the highest LAI value was found with preplant N applied at 100 kg N ha^{-1} plots. In 2012, the plots that received 150 and 200 kg N ha^{-1} preplant applications had significantly higher LAI values, compared to the check N treatment. However, such differences were not found in the plots that received the same amount of N as sidedress application (Fig. 2b). Further, the LAI values at Ottawa in 2012 were nearly twice as large as those measured in 2011 for all the treatments. This higher LAI was probably due to the early

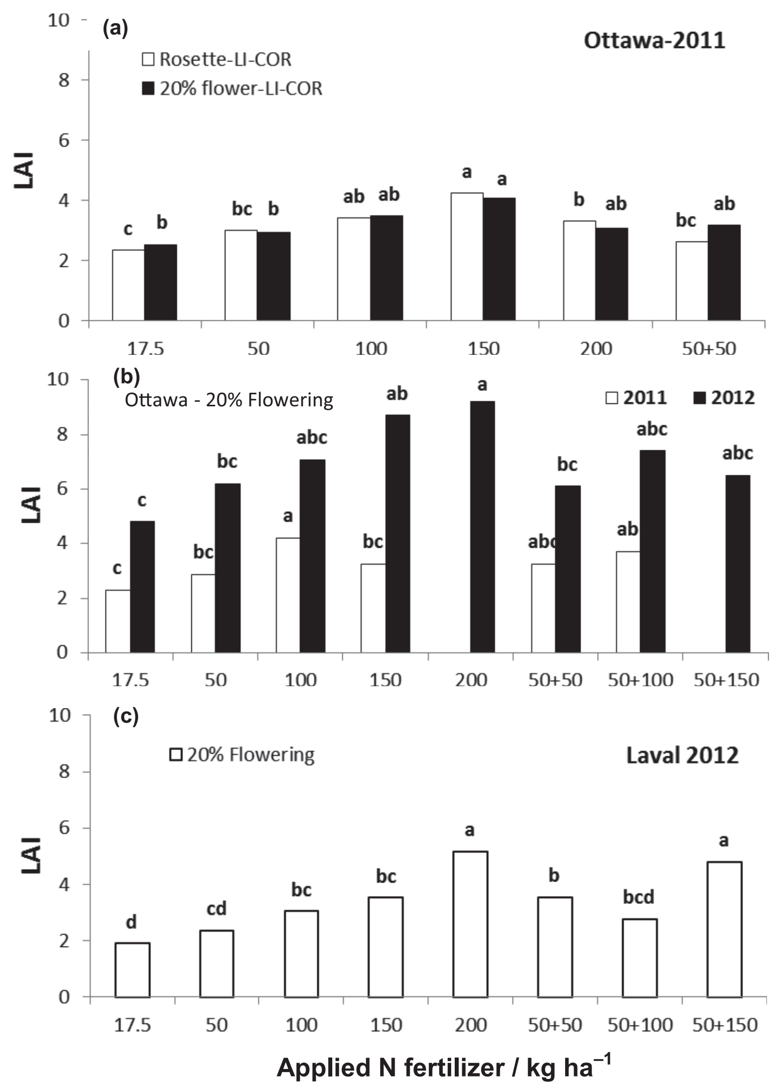

Figure 2: Effects of N-fertilizer application on the leaf area index (LAI) measured by using the LI-COR Plant Canopy Analyzer just before sidedressing of N and at the 20% flowering stage in 2011 in Ottawa, and with Leaf Area Meter at 20% flowering stage in both years in Ottawa, and Laval. Means with different letters within a site-year and growth stage are significantly different according to an *F*-protected LSD test at the 5% level.

spring and favorable warm weather conditions at the 2012 Ottawa site, where March was very warm, with maximum temperatures reaching 24–26°C by the middle of the month, causing the snow to disappear quickly. High temperatures in May (Fig. 1) led to maximum vegetative growth of the crop. At the Laval site in 2012, LAI values increased with increasing levels of preplant and sidedress N applications (Fig. 2c), but there was no difference in LAI with comparable levels of N application, and this suggests that the N sidedress was not adequately utilized at the 20% flowering stage as N released from urea hydrolysis took time. The results of preplant N on LAI are comparable with earlier findings in western Canada and elsewhere (*Allen* and *Morgan*, 1975; *Cheema* et al., 2001; *Kumar* et al., 1997; *Wright* et al., 1988). Generally canola took up and assimilated most of the N at early growth stages for maximum growth and development (*Xing* et al., 1998). The early addition of N helped the crop to increase cell division and cell enlargement, resulting in greater leaf-area development. This leaf-area expansion favored subsequent interception and efficient utilization of solar radiation enhancing overall photosynthetic activities, which ultimately increased accumulation of dry matter in leaves and shoots (*Holmes*, 1980).

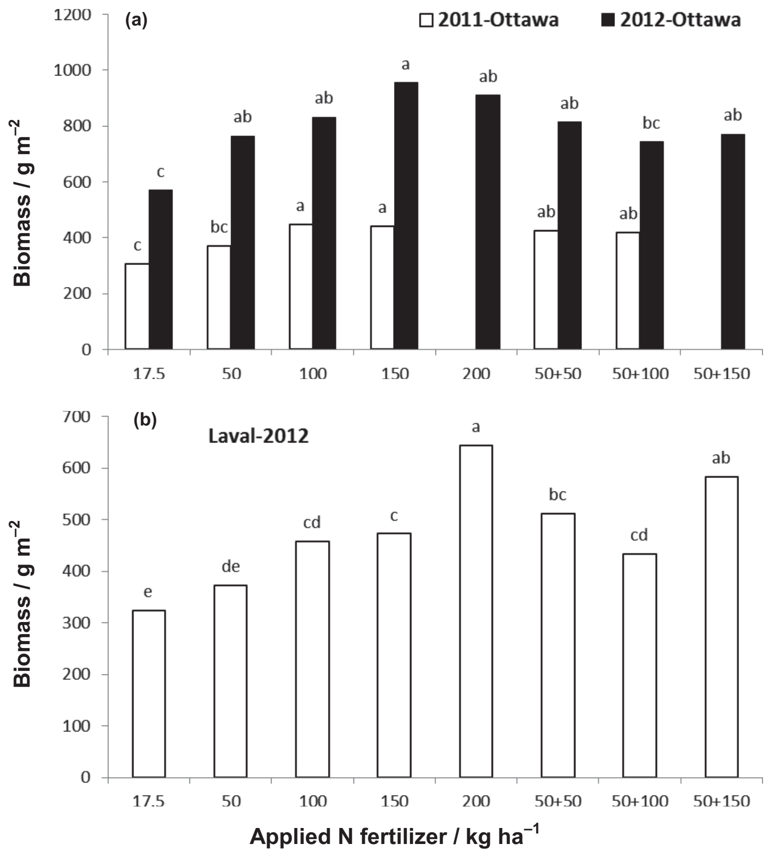

Figure 3: Effects of N fertilizer application on the aboveground plant biomass at 20% flowering for Ottawa in both 2011 and 2012 and for Laval in 2012. Means with different letters within a site-year are significantly different according to an *F*-protected LSD test at the 5% level.

3.2.2 Above ground plant biomass

In both years at Ottawa, plant biomass significantly increased with the increasing amounts of preplant and sidedress N applications compared to the plots that received the control N treatment, with only two exceptions (50N in 2011 and 50N+100N in 2012; Fig. 3a). The lowest plant biomass was in plots with the control N treatment and the highest plant biomass was in plots with preplant application at 100 kg N ka^{-1} in 2011 and 150 kg N ka^{-1} in 2012. While preplant and sidedress N treatments produced similar biomass in Ottawa in 2011, the 2012 plant biomass was higher for preplant treatment at 150 kg N ha^{-1} than for the 50+100 kg N ha^{-1} treatment with sidedress N (Fig. 3a). The reason for higher biomass production with preplant N application than sidedress N application was likely due to the early spring and warm weather conditions which promoted early vegetative growth of the crop in 2012, similar to that observed under dryland farming conditions in Australia (*Hocking* et al., 1997). In addition, for Ottawa in 2012, the progressive increase of N levels from 100 to 200 kg N ha^{-1} in preplant or 50+50, 50+100, to 50+150 kg N ha^{-1} in sidedress did not lead to corresponding increases in plant biomass. Overall for Ottawa, plant biomass with all preplant and sidedress N treatments was 86–117% greater in 2012 than in 2011 and the lowest plant biomass was with the control N treatment and the highest increase was with the 150 kg N ha^{-1} preplant application (Fig. 3a). This higher biomass production in 2012 was obvious, because, the warm weather in 2012 in Ottawa influenced most of the physiological functions of the canola crop.

At the Laval site in 2012, plant biomass production significantly increased with increasing N application, either preplant (except 50 kg N ha^{-1}) or sidedress, compared to the control N treatment (Fig. 3b). The 200 kg ha^{-1} preplant N treatment produced almost twice as much plant biomass as the 0N plots, while there were no significant differences of plant biomass between preplant and sidedress N at the same level. Compared to Ottawa in 2012, plant biomass was low in all treatments at the Laval site (Fig. 3a *vs*. 3b), which is attributed to the differences in soil and climatic factors at these two locations.

3.2.3 Plant height

Plant height is an indicator of the vegetative growth potential of a crop and is both genetically and environmentally determined. In this study, at almost all of the sites and in both years (except Ottawa and Ste. Anne-de-Bellevue in 2012), preplant and sidedress N applications significantly increased canola plant heights compared to the control N treatment (Table 3). Plants receiving preplant N application were significantly taller than the plants that received equivalent amounts of sidedress N for most sites, and the tallest plants were found in plots that received 150 to 200 kg N ha^{-1}. These results clearly indicate that canola plants responded more to preplant N in their early growth stage and sidedress N may have been more available for reproductive growth. However, the Ottawa and Ste. Anne-de-Bellevue sites in 2012 produced no significant difference in plant height between preplant and sidedress N applications and there was no gain in plant height with increasing N fertilizer inputs. This could be attributed to the weather conditions

Table 3: Effects of N fertilizer on plant height at physiological maturity of canola grown at each site in 2011 and 2012.[a]

Nitrogen	**Ottawa**		**Ste. Anne-de-Bellevue**		**Fredericton**		**Canning**		**Elora**	**Laval**
/ kg ha^{-1}	**2011**	**2012**	**2011**	**2012**	**2011**	**2012**	**2011**	**2012**	**2012**	**2012**
0	163 c	124 ab	108 d	116 ab	125 b	116 d	84 c	N/D	99 a	102 f
50	174 bc	124 ab	109 cd	119 ab	131 b	121 cd	97 b	N/D	104 a	107 def
100	187 a	128 ab	113 bc	117 ab	140 a	126 bc	104 a	N/D	106 a	111 bcd
150	191 a	131 a	N/D	118 ab	140 a	129 ab	110 a	N/D	106 a	115 abc
200	–	129 ab	–	121 a	–	134 a	–	N/D	106 a	118 a
50 + 50	175 b	122 b	109 d	113 b	143 a	125 bc	96 b	N/D	103 a	110 cde
50 + 100	188 a	122 b	114 ab	113 b	142 a	123 bc	95 b	N/D	102 a	104 ef
50 + 150	–	131 a	–	117 ab	–	125 bc	–	N/D	106 a	117 ab

[a]N/D, not determined. Means in the same column with different letters are significantly different according to an *F*-protected LSD test at the 5% level.

especially total rainfall and temperature conditions. In Ottawa, June and July months were extremely dry with only 23 mm of rainfall from June 20 to Aug 4, 2012 (Fig. 1). By July 16, 2012, the Ottawa area was in a stage 2 drought and conditions were similar in Ste. Anne-de-Bellevue, which is about 150 km away from Ottawa. Soil moisture decreased throughout the summer from 23.8% at 5 cm and 21.2% at 15 cm soil depth on June 13, to 7.5% (5 cm) and 8.2% (15 cm), respectively, on July 22 through August 5. This likely influenced plant stature. Similar to our observations, *Öztürk* (2010) working in Turkey, reported that increased plant heights with different N sources (ammonium nitrate, ammonium sulphate and urea) and maximum plant heights were found with plants that received 150 kg N ha^{-1}. However, in contrast to our results, *Öztürk* (2010) also reported that plant height decreased at the highest N rate (200 kg ha^{-1}), likely due to the confounding effect of drought on crop response to N.

3.3 Yield components

For most site-years, the addition of N fertilizer significantly increased the following yield components: Branches plant^{-1}, pods plant^{-1}, seeds pod^{-1} and 1000-seed weight (Table 4). This was expected since the application of N fertilizer accelerates crop growth (*Fismes* et al., 2000), thereby facilitating solar radiation interception and the conversion of photosynthates to yield components, including oilseed.

At most site-years, the number of branches per plant and pods per plant increased with increasing rates of preplant and sidedress N application (Table 4). For example in 2011, the branches plant^{-1} significantly increased in the plots that received preplant N (100N and 150N at Ottawa) and sidedress N applications (50N+50N at Ottawa and 50N+100N at Ste. Anne-de-Bellevue), compared to plots that received the control N treatment. In 2012, the number of branches per plant was significantly higher in the plots that received preplant 100 kg ha^{-1} (Ottawa), 150 kg ha^{-1} (Elora), and 200 kg ha^{-1} (Ottawa, Fredericton and Elora) applications and also with sidedress N applications at 50+50 kg ha^{-1} (Ottawa and Laval), 50+100 kg ha^{-1} (Canning), and 50+150 kg ha^{-1} (Fredericton) than the control N treatment. However, in a few cases, the number of branches did not respond to any level of N treatments either at preplant or at sidedress (Fredericton and Canning in 2011 and Ste. Anne-de-Bellevue in 2012). Increasing branch number in response to increasing N application was noted with higher levels of N fertilizer, up to 120 kg ha^{-1} (*Khan* et al., 2002), 150 kg ha^{-1} (*Uddin* et al., 1992), 160 kg ha^{-1} (*Ahmad* et al., 2011), and 200 kg ha^{-1} (*Öztürk*, 2010).

At the Ottawa and Fredericton sites in 2012, preplant N applied at 200 kg ha^{-1} produced more pods per plant than did sidedress application at the same amount of N (50N+150N). In contrast, at Canning in 2012, plots that received sidedress N (50N+100N) had significantly higher pod numbers than the plots that received the same amount of N at preplant. Overall, in most site-years, the number of pods per plant did not differ significantly between preplant and sidedress N application (Table 4).

At the Ottawa and Fredericton sites, the number of seeds per pod increased with increasing level of preplant and sidedress N applications, with the lowest number of seeds per pod in the control N treatment and the highest number of seeds per pod in the plots that received sidedress N at the 50N+100N level. At the Ste. Anne-de-Bellevue site in 2011 and 2012, there was no difference in the number of seeds per pod due to N fertilization (Table 4).

There was no difference in 1000-seed weight between N application and the control N treatment at the Ottawa and Laval sites in 2012, and at Ste. Anne-de-Bellevue and Fredericton in 2011 (Table 4). For other sites-years, while some responses of seed weights to preplant and sidedress N applications were observed, there was no consistent pattern (Table 4). Such large variation in the response of seed weight to N fertility was likely related to the higher LAI and plant biomass, at the flowering stage, but a lower number of seeds set in 2012 due to the severe drought after flowering that occurred at those sites. *Hocking* and *Stapper* (2001) found that N fertilizer had no significant effects on 1000-seed weights, while *Ahmad* et al. (2011) and *Kutcher* et al. (2005) found that 1000-seed weight

Table 4: Effects of N fertilizer on yield components of canola grown at each site in 2011 and 2012.[a]

Nitrogen	Ottawa		Ste. Anne-de-Bellevue		Fredericton		Canning		Elora	Laval
/ kg ha^{-1}	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Branches plant^{-1}										
0	2.5 b	2.4 b	3.2 b	6.0 a	6.0 a	5.0 c	1.8 a	1.8 bc	2.6 b	4.7 b
50	3.0 ab	3.3 ab	3.6 ab	6.0 a	6.0 a	5.5 c	2.4 a	2.2 bc	3.0 ab	5.5 b
100	3.6 a	4.0 a	4.0 ab	6.0 a	8.0 a	5.8 bc	2.4 a	2.7 ab	3.1 ab	5.0 b
150	3.7 a	3.6 ab	3.8 ab	6.0 a	7.0 a	6.3 abc	2.4 a	2.2 bc	3.4 a	5.7 b
200	–	4.0 a	–	6.0 a	–	7.5 ab	–	2.0 bc	3.6 a	6.5 b
50 + 50	3.5 a	4.0 a	3.3 b	5.0 a	6.0 a	5.8 c	2.5 a	1.3 c	3.1 ab	9.2 a
50 + 100	3.3 ab	3.0 ab	4.2 a	5.0 a	7.0 a	6.3 abc	2.7 a	3.3 a	3.3 ab	7.2 ab
50 + 150	–	3.0 ab	–	4.0 a	–	7.8 a	–	2.3 abc	3.2 ab	5.5 b
Pods plant^{-1}										
0	43 b	48 b	60 a	96 ab	121 b	84 c	21 b	25 b	37 b	71 c
50	54 ab	59 ab	74 a	88 b	122 b	94 bc	26 ab	28 b	45 ab	87 bc
100	71 a	68 ab	75 a	133 a	149 ab	99 bc	33 ab	30 b	50 ab	86 bc
150	71 a	72 ab	79 a	126 ab	140 ab	116 b	35 a	27 b	57 a	102 abc
200	–	84 a	–	108 ab	–	146 a	–	32 b	58 a	124 a
50 + 50	68 a	59 ab	69 a	118 ab	123 b	95 bc	21 b	23 b	45 ab	68 c
50 + 100	68 a	60 ab	80 a	102 ab	173 a	103 bc	32 ab	58 a	47 ab	110 ab
50 + 150	–	57 b	–	113 a	–	96 bc	–	31 b	45 ab	101 abc
Seeds pod^{-1}										
0	12 c	19 c	18 a	20 a	N/D	20 c	N/D	N/D	N/D	N/D
50	13 bc	21 bc	19 a	23 a	N/D	20 c	N/D	N/D	N/D	N/D
100	14 bc	23 b	20 a	19 a	N/D	20 c	N/D	N/D	N/D	N/D
150	17 ab	23 b	20 a	21 a	N/D	21 bc	N/D	N/D	N/D	N/D
200	–	23 b	–	18 a	–	24 a	–	N/D	N/D	N/D
50 + 50	14 bc	23 b	18 a	20 a	N/D	21 bc	N/D	N/D	N/D	N/D
50 + 100	18 a	26 a	19 a	20 a	N/D	21 bc	N/D	N/D	N/D	N/D
50 + 150	–	22 b	–	20 a	–	23 ab	–	N/D	N/D	N/D
1000–seed weight / g										
0	3.06 a	3.20 a	2.80 ab	2.93 c	3.49 a	3.24 a	3.5 a	3.00 e	N/D	3.50 a
50	2.94 ab	3.30 a	2.80 ab	2.96 c	3.42 a	3.15 ab	3.29 ab	3.11 de	N/D	3.50 a
100	2.90 b	3.20 a	2.80 ab	3.10 abc	3.37 a	3.14 ab	3.29 ab	3.14 cd	N/D	3.50 a
150	2.95 ab	3.30 a	2.75 b	3.04 bc	3.36 a	3.20 ab	3.28 b	3.14 cd	N/D	3.40 a
200	–	3.30 a	–	2.98 c	–	3.10 b	–	3.30 a	N/D	3.50 a
50 + 50	2.98 ab	3.40 a	2.90 a	3.00 c	3.40 a	3.20 ab	3.45 a	3.13 de	N/D	3.50 a
50 + 100	3.04 a	3.30 a	2.75 b	3.15 ab	3.40 a	3.25 a	3.48 a	3.20 bc	N/D	3.50 a
50 + 150	–	3.10 a	–	3.20 a	–	3.08 b	–	3.27 ab	N/D	3.40 a

[a]N/D, not determined. Means in the same column with different letters are significantly different according to an *F*-protected LSD test at the 5% level.

was in fact reduced with increasing rate of N application. Another possible explanation for this decline might be associated with late maturity caused by N fertilization, which resulted in poor seed filling and a greater proportion of green seeds according to some authors, although not observed in this study. *Cheema* et al. (2001) pointed out that differences in seed weight were related to a short period between anthesis and maturity and, at that time, the supply of assimilates to the pods plays a crucial role in the development of the seed.

Overall, differences in the response of yield components to N applications among site-years could be explained in terms of the differences in the weather conditions when the specific yield components were formed at these locations, and yield components are known to be compensated by each other, within a certain range, in response to environment-induced stress.

3.4 Seed yields

Seed yield of canola is a function of plant density, number of pods per plant, number of seeds per pod, and seed weight. In this study, seed yield positively responded to N fertilizer applications in both years and sites (Fig. 4). In 2011, at all sites grain yield was significantly greater for preplant or sidedress N application than for the check N treatment. The 50N+100N sidedress N treatment resulted in the highest yield at Ottawa (3374 kg ha^{-1}), Canning (3190 kg ha^{-1}), Fredericton (4012 kg ha^{-1}), and Ste. Anne-de-Bellevue (3808 kg ha^{-1}).

At the Canning, Fredericton, and Laval (or St-Augustin) sites, response of seed yield to N application in 2012 was similar to that in 2011 (Fig. 4), with greater yields by 62.3% (1514 kg ha^{-1}) at Fredericton and by 33.7% (442 kg ha^{-1}) at Laval or Canning, due to N application relative to the control N treatment. However, at the Ottawa and Ste.-Anne-de-Bellevue

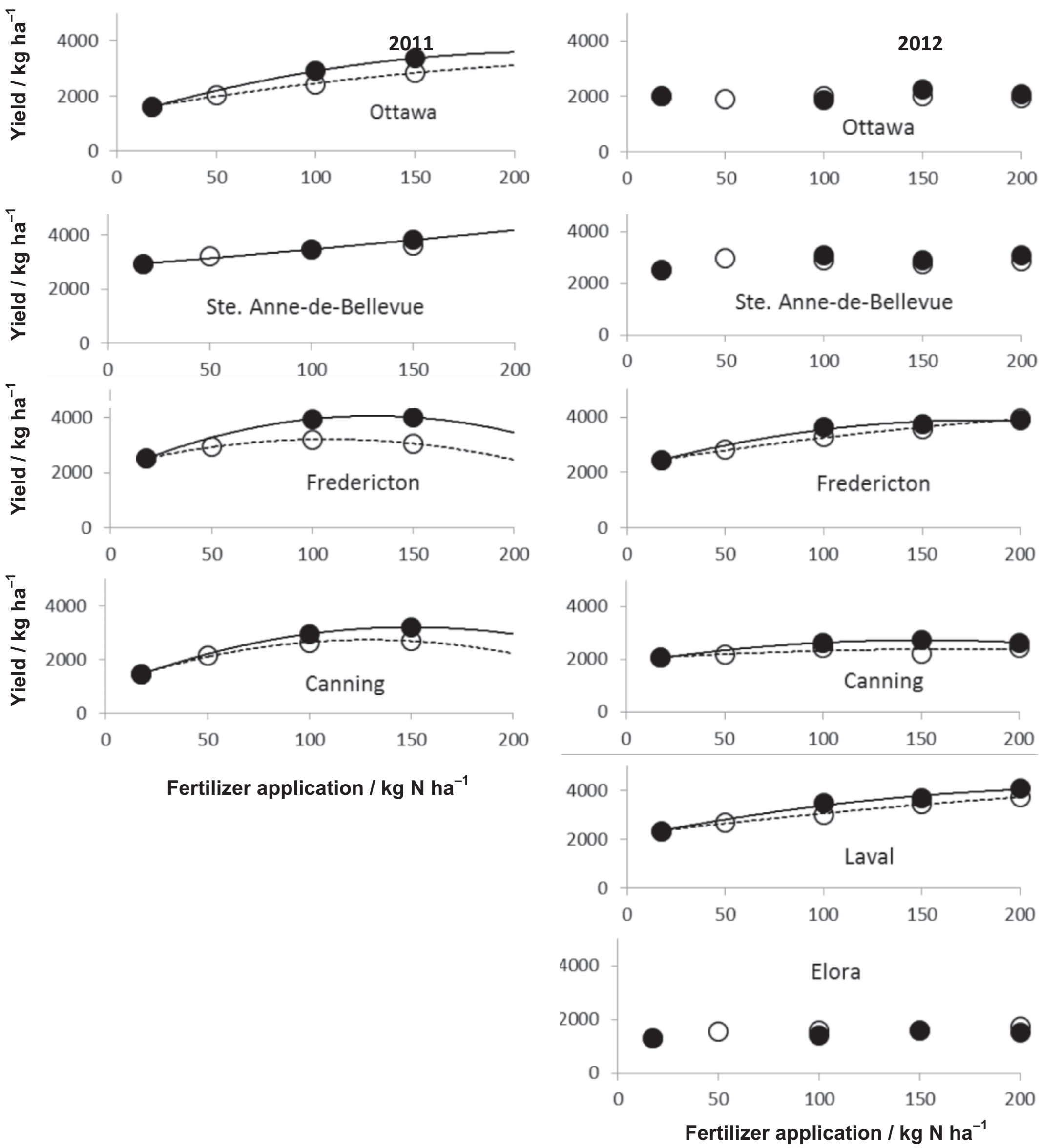

Figure 4: Grain yield of canola as a function of the amount of N fertilizer applied at preplant (empty circles and dashed line) *vs*. sidedress (solid circles and solid line) at each site in 2011 and 2012. Regression lines in the graph indicate significant ($P < 5\%$) responses of yield to N fertilizer rates.

sites, there was no change in seed yield due to N application either at preplant or as sidedress, due the severe drought that occurred at these sites in 2012.

In most cases (except for Elora 2012), there were larger responses of seed yields to sidedress than preplant N application at the same N level (Fig. 4). Soil textures are similar among the tested site-years, with neutral to slightly acidic pH values for most site-years, except for Elora (Table 1). Sidedress of N at Elora in 2012 resulted in a non-significant but greater yield than preplant application, which was likely due to greater potential loss of urea N through NH_3 volatilization for sidedress than for preplant application (*Ma* et al., 2010b). Nevertheless, weather, especially rainfall events and its distribution had the largest impact on canola yield response to N treatments. Both Ottawa and the Ste. Anne-de-Bellevue sites in 2012 encountered severe drought stress from early flowering to seed filling, resulting in no response of yield to neither preplant nor sidedress N application. Overall, our results indicate that sidedress N application appeared to be better utilized by the canola crop and thus produced greater yields than the crop that received equivalent amounts of preplant N. For example, for every kg N ha^{-1} applied canola yields increased on average by 9.7 kg ha^{-1} for preplant N application, and by 13.7 kg ha^{-1} for sidedress N application, in 6 out of the 10 site-years.

Our results are in line with those reported by *Cheema* (1999) and *Zaman* (2003). One of the potential reasons for the effect of sidedress application (*i.e.*, one small portion at preplant and the other portion as in-season application of N fertilizer) on seed yield might be to boost availability of N at the optimum time for uptake in the vegetative and reproductive growth of the canola crop. However, contradictory results were reported in Australia by *Taylor* et al. (1991), who illustrated that split applications of N were no more effective than applying all the required N at seeding. Clearly, the requirement for N fertilizer to achieve maximum seed yield varies according to the environmental variables, including weather, soil type, residual fertility (especially nitrate), management practices, cultivars, *etc*. (*Holmes* and *Ainsley*, 1977), and there is a need for site-specific nutrient best management practices. *Gan* et al. (2007) found that the N rate required to achieve maximum yields of canola in Saskatchewan, Canada, was 135 kg ha^{-1}, whereas *Kutcher* et al. (2005) reported that the maximum seed yield of canola was obtained with 120 kg N ha^{-1} application in northern prairies. Accordingly, choosing the correct rate and timing of N fertilization for a particular site is one of the most critical aspects of successful canola production.

In eastern Canada, using the current cost of N and price of canola, the estimated maximum economic rate of N (MERN) ranged from 105–175 kg N ha^{-1} for preplant N application and 118–233 kg N ha^{-1} for sidedress N application. Clearly, MERN values are affected largely by the site-specific weather conditions and the soil environment. It is difficult to get a general conclusion on the amounts of N that should be applied. However, as a rule of thumb, at the current yield level and average weather, the optimum rate of N on sandy loam or loam soils under the humid climate conditions is between 120 and 150 kg N ha^{-1}, and sidedress N strategy is more efficient than preplant application with savings of 10–20 kg N ha^{-1} to achieve similar canola seed yield. When growth conditions are favorable, it is possible to realize a greater yield potential with the same or slightly more N for sidedress than for preplant N application.

3.5 Effect of sulfur fertilization on growth, yield, and yield components of canola

While growth parameters and yield components did not respond to preplant S application, seed yield was greater with preplant S application at 20 kg S ha^{-1} than the zero S application in 7 of 10 site-years (Table 5). This level of fertilization was based on *Jackson* (2000), who demonstrated that about 20 kg S ha^{-1} application was required to satisfy the high S requirement of canola in the western USA. The highest yield increase of 796 kg ha^{-1} (31%) was observed for the Fredericton site in 2011. The lack of response to S fertilization at the Ottawa and Ste. Anne-de-Bellevue sites in 2012 was probably related to the drought that occurred during the growth season, since SO_4^{2-} transport to the roots by mass flow and diffusion

Table 5: Response of grain yield (kg ha^{-1}) to soil–applied S at 0 and 20 kg ha^{-1} and soil–applied B at 0 and 2 kg ha^{-1} (both at preplanting) and foliar–applied B at 0.5 kg ha^{-1} at the 20% flowering stage.[a]

Nutrient	Ottawa		Ste. Anne-de-Bellevue		Fredericton		Canning		Elora	Laval
	2011	2012	2011	2012	2011	2012	2011	2012	2012	2012
S / kg ha^{-1}										
0	1698 b	2052 a	3274 b	2730a	2576 b	2955 b	2101 b	2116 b	1350 a	2722 b
20	2007 a	1966 a	3372 a	2882 a	3372 a	3257 a	2434 a	2426 a	1511 a	3170 a
B / kg ha^{-1}										
0	1976 b	1963 a	3299 a	2739 a	2995 a	3060 b	2205 a	2166 b	1482 a	2828 b
2 (soil)	2012 b	2052 a	3334 a	2938 a	2970 a	3004 b	2256 a	2311a	1572 a	2837 b
0.5 (foliar)	2199 a	1996 a	3344 a	2715 a	3039 a	3257 a	2360 a	2366 a	1522 a	3197 a

[a]Means in the same column with different letters are significantly different according to an *F*-protected LSD test at the 5% level.

is impeded by low soil moisture. Overall, S application at 20 kg ha^{-1} increased canola yield on average by 15.9% (384 kg ha^{-1}) in 2011 and by 9.2% (214 kg ha^{-1}) in 2012. This is lower than the response to S fertilizer in India, which increased seed yield of *Brassica* species by 30–46% (*Ahmad* et al., 1999). In northern Saskatchewan, *Malhi* et al. (2007) demonstrated that canola seed yield increased sharply with the first 10 kg S ha^{-1} increment, moderately with the second increment and slightly with the third increment of 10 kg S ha^{-1}. Historically, crop production in eastern Canada does not need supplement with S fertilization due to atmospheric deposition. However, with the effective control of acid rain deposition and continued increase in crop yields, S release from soil organic matter mineralization may not be sufficient to meet timely requirement of the crop, and sporadic S deficiency has observed, especially in coarse-textured sand or sandy loam soils (K. Reid, pers. comm.). Therefore, further studies to optimize the S-fertilizer rate on a site-specific basis are warranted for canola production in eastern Canada.

3.6 Effects of boron on growth, yield, and yield components of canola

In most site-years, there was no change in yield and yield components when plots received soil-applied B at 2 kg ha^{-1} rate (2B), compared to zero B application (Table 5). Canning was the only exception, where preplant soil applied-B in 2012 resulted in a 6.7% yield increase (144.6 kg ha^{-1}). However, the significant response of canola to foliar B fertilization at Canning in 2012 as well as 3 other site-years (Table 5) indicates that B fertilizer was beneficial at those sites, which either lacked sufficient soil B or the plant was not able to acquire soil B at the right time to fulfill its physiological needs for this element. Canola response to foliar B application resulted in yield increase of 11.3% (223 kg ha^{-1}) at Ottawa (2011), 6.4% at Fredericton (2012), 9.2% at Canning (2012) and 13% at Laval (2012; Table 5). These results indicate that the canola plants acquired B more efficiently through their leaves than through their roots, and B fertilizer should be foliar applied to achieve a positive yield response of canola. Soil-applied B tends to bind with the soil organo-minerals and, therefore, was not be plant-available. In general, there is a narrow range of soil-extractable B concentration that will optimize crop growth, and B released from soil organic matter decomposition can meet the requirement of many crop plants in eastern Canada (*Subedi* and *Ma*, 2009). However, the canola crop has a larger requirement at flowering and pod/seed set than other crops (*Hammond*, 2011). We speculate that the site-specific response of canola yield to foliar B application is likely due to the fact that seasonal release of B from decomposition in sandy loam soils may not meet the timely requirement for B by the crop. There are two other possibilities, the first being that soil-applied B was bound to soil organo-minerals, and second that the plant-available forms of this nutrient (boric acid, H_3BO_3 is the predominant form in soil solution) are susceptible to leaching in coarse-textured soils of humid regions. As a neutral species, boric acid may be readily transported through soil solution due to lack of steric hindrance and lack of charge repulsion. As at the present, there is no reliable soil or plant tissue testing method for predicting economic response to applied B fertilizer, but a tissue test is likely preferred (*Hammond*, 2011). An emerging research priority is in developing diagnosis tools and implementing B-management technologies for canola in eastern Canada.

3.7 Correlations of canola seed yield and yield components

Seed yield of canola is a function of the number of branches per plant, number of pods per plant, number of seeds per pod, and mean seed weight. Partial correlation coefficients of canola seed yield and other plant traits are given in Table 6.

Table 6: Partial correlation coefficients of canola seed yield and yield components or plant traits in each site-year, determined with MANOVA based on n = X observations per site-year.[a]

Location	Year	Plant Height	Harvest Index	1000 Seed weight	Branches / plant	Pods / plant	Seeds / pod
Ottawa	2011	0.48**	0.12	0.32**	0.16	0.30*	0.34**
	2012	0.40*	0.55**	0.38*	0.01	0.10	0.02
Ste. Anne-de-Bellevue	2011	0.34**	−0.10	−0.18	0.01	0.06	0.05
	2012	0.66**	0.05	−0.21	−0.02	0.20	−0.25*
Fredericton	2011	0.67**	−0.06	0.05	0.19	0.29	N/D
	2012	0.49**	0.07	−0.52**	0.17	0.18	0.03
Canning	2011	0.27*	0.03	−0.25*	0.10	0.24*	N/D
	2012	N/D	0.63**	0.44**	0.16	0.28*	N/D
Laval	2012	0.54**	0.18	−0.19	0.15	0.39**	N/D
Elora	2012	0.10	−0.02	N/D	0.15	0.31**	N/D

[a]** Significantly different at the 5% and 1% probability levels, respectively. N/D: Not determined.

These results show that grain yield was positively correlated with some of the measured traits. For example, for 9 of the 10 site-years, except Ottawa in 2012, plant height was significantly correlated ($P \leq 0.1\%$) with seed yield. Other yield components, such as pods per plant, seeds per plant and 1000-seed weight (TSW) were also significantly correlated ($P \leq 0.1\%$ and $P \leq 1\%$) with seed yield in some site-years (Table 6). The inconsistent correlations between seed yields and yield components across site-years were probably due to the overarching impact of environmental conditions (rainfall, temperature, radiation, humidity, wind, *etc*.) during the specific yield formation stages at each site. When grown in stressful environments, canola responds physiologically by altering energy allocation to various yield components, leading to a compensatory response among traits that contribute to the final seed yield.

3.8 Seed quality

In 2011 and 2012, seed quality parameters were measured for the Ottawa site only. In 2011, the percentages of distinctly green seeds were not significantly different among treatments (data not shown). However, N application either as preplant or sidedress tended to produce higher percentages (up to 2.4%) of brown, tanned, and empty seeds than the zero N (0.7%). The percentage of damaged seeds (a total of the green, brown, tanned, and empty seeds) also increased significantly with increasing amounts of preplant and sidedress N applications compared to the check N treatment, and the highest percentage of damaged seeds (up to 3.5%) was unexpectedly found in the plots that received 50N+50N sidedress N. Nevertheless, total irregular and damaged seeds for all treatments were below 5%. In 2012, there were no green seeds for any of the treatments and no N fertilizer effect on the percentage of damaged seeds. In general, excessive soil N supply may lead to green seed problem due to N's role in chlorophyll synthesis. Still, considering the N fertilizer levels were tested in this study for 2 years, it was encouraging to note that there were fewer than 2% distinctly green seeds and less than 5% damaged seeds across all fertilizer treatments. Hence the seed quality in both growth seasons could be considered as grade No. 1 canola and the N fertilizer rates selected appeared to be suitable for producing high-quality canola, without generating an excessive N supply at these sites in eastern Canada.

4 Conclusions

Sidedress application appeared to meet the N requirement of canola more efficiently during the rapid growth and development stages and, thus, displayed greater efficiency in most cases. Preplant S application at 20 kg S ha^{-1} was effective at promoting yield in 7 of 10 site-years. When B was required by the crop (4 of 10 site-years), foliar B application at the 20% flowering stage was more effective than soil-applied B, indicating that the canola plants acquire B through their leaves more efficiently than through their roots. This may indicate that soil-applied B was bound to the soil organo-minerals, or that it was susceptible to leaching from coarse-textured soils in the humid regions where this study was conducted, and therefore not plant-available. The challenge remains to develop site-specific fertilizer applications that deliver ample N, S, and B for canola production considering that unfavorable weather conditions may cause nutrient losses and constrain canola growth at key development stages in eastern Canada.

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