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Complete List of Authors:	Herath, Aruna; Agriculture and Agri-Food Canada, Ottawa Research and Development Centre Ma, Baoluo; Agriculture and Agri-Food Canada, Ottawa Research and Development Centre Shang, Jiali; Agriculture and Agri-Food Canada; Liu, Jiangui; Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Ottawa, Ont., Canada Dong, Taifeng; Agriculture and Agri-Food Canada Jiao, Xianfeng Kovacs, John; Nipissing University Walters, Dan; Nipissing University
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On-farm spatial characterization of soil mineral nitrogen, crop growth, and yield of canola as
affected by different rates of nitrogen application

A. Herath¹, B. L. Ma^{*1}, J. Shang¹, J. Liu¹, T. Dong¹, X. Jiao², J. M. Kovacs², and D. Walters²

¹Agriculture and Agri-Food Canada, Ottawa Research and Development Centre, Ottawa, ON;

²Department of Geography, Nipissing University, North Bay, ON

* Corresponding author (baoluo.ma@agr.gc.ca)

Short title: Spatial patterns of soil N supply and canola crop growth

Abstract

Understanding the spatial variability of soil mineral nitrogen (SMN) and crop growth is an important step for implementing precision nitrogen (N) management technologies for canola production. A three-year field experiment in Ontario investigated the within-field spatial variability of SMN in relation to growth parameters and yield. Each year large strips in a commercial field were randomly assigned a preplant N treatment (0, 50, 100, 150 kg ha⁻¹), with three replicates of each. Our data showed that SMN varied widely among field-strips receiving different treatments and also within strips receiving the same N rate, indicating significant spatial variability in N availability at the field- and strip-scale. Some crop measurements exhibited wide variations in parallel with the SMN dynamics. At the early flowering stage, SMN contents displayed a strong relationship with plant height and branch numbers. While grain yield showed a positive response to N, the inconsistent yield increase with increasing N supply was likely due to the inherent variations in soil N supply among years and fields, indicating an inefficient use of the uniformly-applied preplant fertilizer N by the crop. The strong associations between SMN

and crop parameters or yield provided a substantial evidence for implementing in-season variable rate N application.

Key words: Canola or oilseed rape; in-season nitrogen application; precision farming; soil mineral nitrogen dynamics; spatial variability; yield monitoring

Introduction

Since N is often the limiting nutrient for high N demanding crops such as canola (*Brassica napus* L.), N fertilization is the most decisive factor to achieve optimum grain yields and profits. However, the availability of N to crops involves complex processes controlled by edaphic, environmental and management factors. Many researchers report that soil properties can influence the availability of soil mineral nitrogen (SMN) to crop, so crop response to N is spatially variable (Basso et al. 2013; Cambardella et al. 1994; Jaynes et al. 2011; Jokela and Randall 1989; Ma et al. 2014; Khosla et al. 2002; Solie et al. 1999). Therefore, crop N requirements can vary significantly among fields with same crop (Scharf et al. 2002) or within the same field of crops (Blackmer and White 1998; Ma and Dwyer 1999; Ferguson et al. 2002). Managing this spatial variability is vital to using fertilizer N efficiently; it has been widely recognized as an important field management issue (Basso et al. 2013; Delgado and Bausch 2005; Ferguson et al. 1996; Gotway et al. 1996; Hergert et al. 1996; Jaynes et al. 2011; Ma et al. 2014; Raun et al. 2002; Redulla et al. 1996; Roberts et al. 2012; Scharf et al. 2002, 2011; Shanahan et al. 2008).

Nitrogen fertilizer management in a cool and humid environment as found in eastern Canada is even more important due to the significant spatial and temporal variability of both soil

N supply and crop growth factors in the field (Ma and Dwyer 1999). However, the spatial variation in soil properties is not generally considered in traditional N-fertilizer application; it is often based on a single rate of application across the entire field regardless of soil type and other variables. When N is applied at a uniform rate, parts of the field could be under-fertilized, resulting in N deficiency that may retard the plant growth by reducing photosynthesis (Khamis et al. 1990) and lower yields with low economic returns (Ma et al. 1996, 2005, 2010, 2014; Corp et al. 2003). In contrast, parts of the field could be over-fertilized, resulting in higher vegetative growth that may lead to an increased risk of lodging (Wu and Ma 2016), delayed maturity and greater susceptibility to diseases and weed problems. Additionally, the over-fertilized field would have surplus N left in the soil at the end of the growing season (Ma and Herath 2016). The presence of surplus N in the soil-plant system has been identified as the main source of nitrate-N (NO_3^- -N) accumulation in the soil (Vyn et al. 1999). Nitrate can get into the downstream water system through leaching or surface runoff causing environmental pollution and posing health risks to humans and animals (Huggins and Pan 1993; Raun et al. 2002; Matson et al. 2002; Haller et al. 2016). Over fertilization is also the main cause of N_2O emissions from corn fields (Ma et al. 2010). There are economic and environmental benefits to using site-specific N application and meeting the crop N requirements. The challenge is tailoring application rates of N fertilizer at the right location, at the right physiological stage of crop growth (Ma and Herath 2016). Therefore, diagnostic tools are needed for understanding the field spatial variability and accounting for spatial patterns of soil N supply potential to estimate the exact crop N requirement for making improved N management decisions.

Precision agriculture technology can help growers of high value cash crops cope with the variability of N in crop fields for site-specific N management. For example, yield monitoring and

mapping can help inform N management decisions. Yield monitors that are mounted to the grain harvesters provide a continuous recording of yield over the harvesting field. Moreover, yield monitors that include the global positioning system (GPS) receiver and sensors that are designed for measuring grain moisture, grain flow rate, and crop yield simultaneously as they harvest, provide the information on the spatial variability of the crop field in that particular year. Collectively, such detailed yield map information would give producers an option to implement variable-rate N fertilizer applications, based on the site-specific yield potentials.

Research using yield mapping technology is mostly applied with advanced mechanization and large scale operations of cereal crop production (Modal and Basu 2009). There appear to be no studies assessing the applicability of yield monitors in canola crop production. The purpose of this study is to better understand the interactive effects of SMN supply and crop growth parameters on grain yields in commercial canola fields. The specific objectives were to: (1) assess the effects of N fertilizer application on the spatial patterns of SMN, crop growth parameters and grain yield of canola; and (2) determine the dynamic relationships among SMN, plant growth parameters and yield.

Materials and Methods

Site description

For three years (2012-2014), canola field experiments were conducted at a commercial farm in Verner, northeastern Ontario, Canada (46° 23'N, 80° 06'W). The soil textures vary from clay loam to loam, and the soil characteristics are presented in Table 1. Although poor drainage is a potential issue in this area, tile drainage and an extensive network of municipal drains help crop

productivity of the area (Wilson et al. 2014). The climate is cool and humid with a relatively short growing season of approximately 2268 to 2569 growing-degree days (GDD), from 1 May to 30 September, on a base temperature of 0 °C. Although the cumulative GDDs were similar among the three years, the GDD values from seeding to harvest of the canola crop in 2014 were much smaller (1510) than 2096 GDDs in 2012 and 1978 GDDs in 2013. Due to excessive rainfall during the late part of grain filling period, the crop did not reach full maturity in 2014.

Treatment and experimental design

In each year, a large new commercial field was chosen for the study. The field was divided into 12 large strips, with each strip of 300 - 500 m long and 48 - 64 m wide. To explore crop response to different amounts of N application, four N application treatments (i.e. 0, 50, 100, and 150 kg ha⁻¹), as compound granular fertilizers (32-10-10.3) specially formulated for canola, were randomly assigned to the field-strips with three replications (Shang et al. 2015). At preplant preparation, field was chisel ploughed to a depth of about 15-20 cm in the fall, and cultivated to a depth of 10-15 cm in the spring before broadcasting fertilizer N at the target application rate for each N treatment strip. Canola (InVigor 5440) seeds were sown at the recommended seeding rate of 5.6 kg ha⁻¹ on 5 May 2012, 15 May 2013 and 30 May 2014 (Table 1). The crop was managed according to the Ontario Provincial Agronomy Guide for Field Crops (OMAFRA 2009). Both preplant and post-emergence herbicides (Liberty 200SN at a rate of 2.5 L ha⁻¹) were used to keep the field free of weeds.

Data collection

Soil sampling

To determine the within-field soil variability, GPS-guided multiple sampling locations were preselected within each large strip before planting for all three years. Soil samples were collected at 0 - 30 cm depth shortly before N application and prior to planting, and again at the early flowering stage in all years. In 2012, soil samples were also taken within one week after crop harvest. The sample points were located along the centre line within each strip (300-500 m long) at about 100 m distance (72, 30 and 24 sample points in 2012, 2013 and 2014, respectively). Two soil cores were collected and thoroughly mixed to obtain a composite sample at each sample location. The initial soil samples were analyzed in a chemistry lab to obtain basic soil properties including pH (1:1 with water), soil particle size analysis (hydro meter method), organic matter (Walkley-Black acid digestion method), mineral N (2 M KCl extraction), available P (sodium bicarbonate extraction) and soil test K with ammonium acetate extraction method (Table 1). The samples at early flowering and at post-harvest were also extracted with 2 M KCl solution and analyzed for NO_3^- -N and NH_4^+ -N concentrations with a flow injection auto analyzer (QuikChem® 8000 Flow Injection Analyzer, Zellweger Analytics, Inc., Lachat Instruments, Milwaukee, WI, USA).

Crop data collection

During the growing season, crop phenology was recorded based on the BBCH-identification keys of oilseed rape (Lancashire et al. 1991). Plant growth parameters, including plant height (ground to the tip height of each of 10 plants), aboveground biomass, and plant density were determined at GS 32 (rosette), early flowering (GS 62), pod formation (GS 71), and physiological maturity (GS 89). At each sample location, the number of plants within a 1-m row

was recorded, and aboveground plant biomass was determined. Plant leaf area within the 1-m row was also determined destructively, using a leaf area meter (LI-3100C, Li-Cor, Lincoln, NE) at the GS 32 and GS 62 stages, and leaf area index (LAI) was calculated. At GS 89, samples from two 1-m rows were taken for determining the final plant height, the number of branches per plant, number of pods per plant, and number of seeds per pod.

In 2012, the ground plant samples and the whole canola seed samples were digested using the Kjeldahl digestion method (AACC 1983) and analyzed for N concentrations, with a flow injection auto analyzer (QuickChem® 8000 Flow Injection Analyzer, Zellweger Analytics, Inc., Lachat Instruments, Milwaukee, WI, USA). Nitrogen content of stems and seeds were calculated as the product of N concentration by its biomass, and the data was used to calculate crop N uptake.

Yield data

In 2012 and 2013, final grain yields were measured using the yield monitor system of Case IH Advanced Farming Systems (AFS). The spatial yield monitor readings were stored on a memory card, the data was traced with the Farm works® Trac & Site software and exported as yield maps in ESRI shapefile format. Raw yield point data were cleaned by eliminating data from 5 m over-travel areas and removing outliers to get most reliable yield monitoring data for statistical analysis. In 2014, grain yield monitoring data were not collected due to an extended period of rain during harvest that prohibited combining the field, and the crops started to rot. However, yield data were collected by hand from all the sampling locations on 26 August and used in the analysis. It was reasonable to compare treatment effects on the hand harvested yield within 2014

growing season, but the yield data would not represent the yields recorded with the yield monitor at full maturity, as those in the other years.

Data Analysis

Descriptive statistics (mean, minimum and maximum, standard deviation and coefficient of variation) were calculated using the Excel software to describe the data distribution among field strips within a given N rate and year. Analysis of variance (ANOVA) was conducted using the STATA software to determine the effects of different rates of N application on the spatial variability of SMN contents, crop measurements, and grain yield. Within-field spatial variability of SMN was captured using two statistical approaches, the coefficient of variation (CV) and significance of the means claimed with ANOVA. The Pearson correlation coefficients were calculated to determine the relationships between the SMN and measured crop variables, including yield and yield components. The relationship between grain yield and the N application rates was examined with regression analyses.

Results and Discussion

Effect of nitrogen application on soil mineral nitrogen

In all three years, SMN contents at different sampling times showed large spatial variations among the field-strips that received different N treatments, as well as within field-strips that received the same N treatment, including the unfertilized control strips. The dynamic responses of the SMN to different rates of N application and the spatial variations during the crop growing season in all three years are discussed in detail below.

Soil mineral nitrogen at preplant

The SMN at preplant did not differ among field-strips that received different rates of N compared with the SMN in the control in each year (Table 2). However, preplant SMN contents varied largely among the three years. The lowest SMN contents were in 2013 (mean values ranged from 5.3 to 5.5 $\mu\text{g g}^{-1}$) and the highest SMN contents were in 2012 (mean values ranged from 8.4 to 9.7 $\mu\text{g g}^{-1}$), while in 2014 the SMN mean values ranged from 7.0 to 9.2 $\mu\text{g g}^{-1}$ (Table 2). Such differences in SMN contents before planting were likely due to the different preceding crops (wheat for 2013 and 2014, and pasture for 2012), soil characteristics (Table 1) and weather conditions, mainly non-growing season precipitations (Liang and MacKenzie 1994) in these canola fields. The highest SMN contents in 2012 likely resulted from the combination effect of warmer conditions in early spring (April and May) and the preceding forage crop for that year.

The CV values of the SMN contents (Table 2) at preplant indicate different degrees of spatial variation among these field-strips. For example, in 2012, the CV values for SMN varied from 19.3% to 27.1 %, while they were from 11.5% to 35.1 % in 2013 and from 24.6% to 42.0% in 2014.

Soil mineral nitrogen at early flowering stage

The early flowering stage (i.e. about 20% of all buds raceme flowering) is the most critical period for pod and seed set. The SMN contents at this stage were numerically higher than the corresponding preplant SMN contents in all three years (except for SMN in the 2013 control strips). Such increases in the SMN contents may be attributable to fertilizer N addition, as well as

N released from soil organic matter mineralization (Johnson and Raun 2003). The SMN contents consistently increased with increasing rates of N application (Table 2). In 2012, the SMN contents in field-strips that received N treatments were significantly higher than the control strips, and the field strips of the 150N treatment (the highest level of N treatment in the experiment) displayed the highest SMN content compared with those of the 50 kg ha⁻¹ N and 100 kg ha⁻¹ N treatments. In 2013, the 150 kg ha⁻¹ N treated field-strips also displayed significantly higher SMN contents than the other treatments. In 2014, the SMN contents did not differ significantly among the treatments, yet the SMN contents in all three N treated field-strips were higher than the SMN content in the control strip (Table 2). In 2013, there were significant differences in SMN among the replicated field strips of 150 kg ha⁻¹ N treatment (Fig. 1e), yet no such differences were found in other N treatments or in other years (Fig. 1b and 1g).

In 2012, field-strips that received three rates of N application had almost similar variations in SMN contents (CV ranged from 17 to 25%) as those of the control field-strips (CV 23%; Table 2). However, in 2013, larger variations in SMN levels were observed in the field-strips that received N treatments (CV ranged from 42 to 48%), compared with the control (CV of 14%). Furthermore, the variation in SMN contents (Fig. 2) increased throughout the season in field-strips that received N treatments, while the variation in SMN in the control field-strips stayed almost the same. Similarly in 2014, SMN levels in all N treated field-strips showed large spatial variation (CV ranged from 32 to 38%) compared with the control (CV of 8%). Comparing SMN levels at early flowering stage in response to different N treatments, the highest spatial variation in SMN levels was found in 2013 and the lowest spatial variation was in 2012. However, spatial variations in SMN contents in the control field strips were lower in 2014 than in other years (Table 2).

Soil mineral nitrogen at post-harvest stage

In 2012, the post-harvest SMN data were collected. Regardless of N treatments, the SMN contents at the post-harvest stage were lower than at early flowering stage (Table 2). This reduction in SMN between early flowering and post-harvest could be associated with the crop uptake (Ma and Zheng 2016), the reduction of soil N released from organic mineralization and N losses through leaching. The mean SMN values at post-harvest ranged from 11.6 to 20.6 $\mu\text{g g}^{-1}$ among the N-applied strips, compared to 8.7 $\mu\text{g g}^{-1}$ of the unfertilized control strips. Among all the treatments, the highest level of SMN was found in the 150 kg ha⁻¹ N treated strips, indicating a high risk of off-season NO₃-N leaching (Ma et al. 2010; Schepers et al. 1991).

Field-strips that received 150 kg ha⁻¹ N treatment showed the largest spatial variation in SMN contents at post-harvest stage (CV of 58%). That was almost twice as much as the spatial variation of SMN in the 100 kg ha⁻¹ N treated field-strips (CV 29%), and the control field-strips (CV 27%), and also two times greater than the spatial variation in 50 kg ha⁻¹ N treated field-strips (CV 18%). In addition, the spatial variability in SMN content increased from early flowering to post-harvest stage for comparable N treatments including the control. These variations were higher in high rates of N treated field-strips (100 kg ha⁻¹ N and 150 kg ha⁻¹ N treatments), suggesting that the spatial variability in SMN was largely influenced by higher rate of N applications (Ma and Dwyer 1999) and those variations were substantial at the end of the growing season.

The Pearson correlation coefficient values (Table 5) indicate that the N application rates had strong positive relationships with SMN contents throughout the cropping. In 2012, the SMN contents showed significant and strongest relationships with the N application rate at early

flowering (0.82^{***}), and at post-harvest (0.52^{**}). In 2013, SMN contents at early flowering also showed significant association with N application rate (0.75^{***}), whereas the relationship at early flowering was insignificant (0.37) in 2014 (Table 5). The latter was likely associated with frequent rainfalls and higher soil moisture levels at sampling in 2014 than in other seasons, and the yield potential was therefore restricted in 2014.

Effects of nitrogen application rates on crop growth parameters

Plant height did not display a large spatial variation among the field-strips that received a given rate of N (Table 3). Even among the field-strips that received different rates of N, the CV values of the plant height ranged from 3.8 to 6.3% in 2012, 4.1 to 9.4% in 2013 and 1.9 to 9.4% in 2014, including the control (CV values ranged from 5.7 to 13%). In all three years, plant height positively responded to N applications, and plants in all rates of N-treated field-strips were significantly taller, compared with the plants in the control field-strips (Table 3). As expected, the tallest plants were found in the 150 kg ha^{-1} N treated field-strips in both 2012 and 2013. In 2014, no significant difference in plant heights was found among the field-strips that received different N treatments. This was because compared with previous two years of this study, the delayed planting (due to cool temperature in May) and wet weather conditions throughout the canola growing season in 2014 may have negatively impacted canola crop growth and soil N transformation processes. Given the weather conditions, crop N uptake may have become the secondary factor in determining plant heights.

LAI is a measure of the potential for solar radiation interception at the field level. In this study, LAI showed a large spatial variation across the field-strips that received different N treatments (CV values ranged from 13 to 35% in 2012, 18 to 43% in 2013, and 27 to 37% in

2014), as well as in the control field-strips (CV values ranged from 23 to 47% across three years) (Table 3). Even though the highest spatial variation in LAI was found in the control field-strips (CV of 47%) in 2012, the CV values in LAI increased with increasing N rates. In all three years, the spatial variations in LAI were inconsistent with N application rates, and the highest spatial variation was found in the field strips that received 100 kg ha⁻¹ N treatment in 2013 (CV of 43%) and 50 kg ha⁻¹ N treatment in 2014 (CV of 37%), while in the control strips in 2012.

As expected, LAI values in all N treated strips were numerically higher in all three years compared to the LAI values in the control field-strips (Table 3). These results are consistent with our earlier findings (Ma et al. 2015) on canola grown in eastern Canada. In 2012 and 2013, field-strips that received 150 kg ha⁻¹ N treatment had a significantly higher LAI, compared with both the control field-strips and the lower rates of N treated field-strips. This can be explained as higher rates of N applied at preplant could have contributed to an increased cell division and cell enlargement, resulting in greater leaf area development. In 2014, the field-strips that received 50 kg ha⁻¹ N treatment had a significantly higher LAI compared to the control. However, LAI did not display a significant difference among N treatments, likely due to the effect of cold and wet weather conditions which may have hindered crop growth and uptake of the applied N by the canola crop.

Similar to LAI, large spatial variations in plant dry biomass was also observed among field-strips that received different N treatments (CV values ranged from 12 to 28% in 2012, 30 to 38% in 2013, and 20 to 24% in 2014), as well as in the control (CV values ranged from 18 to 36% across these three years). However, spatial variation in plant biomass was inconsistent with N application rates (Table 3). For example, in all three years, the highest spatial variation in plant biomass was found in the field-strips that received 50 kg ha⁻¹ N treatment (CV of 28, 38 and 24%

for 2012, 2013 and 2014, respectively), and the lowest spatial variation in plant biomass differed from year to year: 150 kg ha⁻¹ N treated field-strips in 2012 (CV of 12%) and in 2013 (CV of 30%), and in 100 kg ha⁻¹ N treated field-strips in 2014 (CV of 20%).

In all three years, plant biomass production in all N treated strips were numerically higher than the plant biomass production in the control field-strips, which had the lowest plant biomass production. Although the plant biomass was not significantly different among the N treatments both in 2012 and 2014, the field-strips treated with the N rates of 100 and 150 kg ha⁻¹ in 2013 had significantly higher plant biomass production compared to the biomass production in the control field-strips.

Generally, crop growth parameters such as plant height, LAI and aboveground plant biomass are good indicators of the vegetative growth potential of canola crop, due to their significant influence on grain yield (Ma and Zheng 2016). Since the crop growth is closely linked with the amount of solar radiation captured by the leaves, the size of the leaf area substantially influences the plant biomass production. Especially at early flowering stage of canola, leaf area affects the development of the plant's overall sink capacity, pod set and seed development, and ultimately final grain yield. Therefore, the effects of N application on the spatial variability of crop growth parameters are an important consideration for canola N management decisions. The inconsistent relationships between N application rates and growth parameters including yields across growing seasons can be contributed to the prevailing weather conditions, mainly rainfall amount and its distribution across the season, which subsequently influenced soil moisture conditions and soil N availability, both spatially and temporally. For example, the negative impact of drought that occurred during the growing season was often exaggerated by N application (Ma et al. 2015).

Effects of nitrogen application rates on yield components

Large spatial variations in plant density (plants m^{-2}) were observed in field-strips that received different N treatments (CV values ranged from 24 to 29% in 2012, 14 to 42% in 2013, and 11 to 17% in 2014) (Table 4). In the control field strips, the CV values ranged from 24 to 33% across the years. Both in 2012 and 2014, the highest spatial variation in plant density was observed in the control field-strips (CV values of 33 and 24%, respectively), while in 2013 the highest spatial variation in plant density was found in 100 kg ha^{-1} N treated field-strips (CV of 42%). Overall, the mean values of plant density ranged from 63 to 125 plants m^{-2} across the years, regardless of N treatments.

Number of branches per plant showed a large spatial variation (CV values ranged from 16 to 28% in 2012, 21 to 43% in 2013 and 22 to 44% in 2014) regardless of the N treatments (Table 4). The lowest spatial variation in branch numbers was found in the 100 kg ha^{-1} N treated field-strips in all three years (CV values of 16, 21, and 22% for 2012, 2013 and 2014, respectively), and the highest spatial variation found in 50 kg ha^{-1} N treated field-strips in 2012 (CV of 28%), control field-strips in 2013 (CV of 43%), and 150 kg ha^{-1} N treated field-strips in 2014 (CV of 44%). As expected, the number of branches per plant were numerically higher in all the N treated field-strips, while the lowest branch numbers found in the control field-strips in all three years. Both in 2012 and 2013, the highest branch numbers were found in the 150 kg ha^{-1} N applied field-strips, indicating the significant impact of the high rate of N application on the growth of branch numbers.

In this study, the pod number per plant also had large spatial variation in the field-strips that received different N treatments in all three years (CV values ranged from 16 to 37% in 2012,

20 to 39% in 2013, and 28 to 36% in 2014). The field-strips that received the highest rate of N ($150 \text{ kg ha}^{-1} \text{ N}$) had numerically the largest CV values (spatial variation) in pod numbers (CV values of 37, 39 and 36% in 2012, 2013, and 2014). In general, the number of pods per plant was numerically higher in the N treated field-strips compared with the control field-strips in all three years.

Compared with the spatial variability of the above yield components, the number of seeds per pod displayed a small spatial variation with different N treatments (CV ranged from 6 to 13% in 2012 and 5 to 9% in 2013). Overall, results of this study demonstrated that in all three years, the least spatial variation was observed in plant height and seed numbers per pod, and the highest spatial variation was observed in LAI, plant biomass, and plant density. In addition, spatial variability in LAI (only in 2012), and pod number (only in 2013) increased with increasing N application rates, partially attributed to the varying conditions from year to year.

The Pearson correlation coefficient values indicate that in all three years, most of the crop parameters showed positive relationship with N application rates (Table 5). For example, in all three years, plant height (0.85^{***} , 0.71^{***} and 0.55^{*}), LAI (0.70^{*} , 0.74^{***} and 0.58^{**}) and plant biomass production (0.41^{*} , 0.61^{***} and 0.51^{*}) showed significant relationship with N application rates in 2012, 2013 and 2014, respectively. In addition, branch numbers (0.56^{**}), pod numbers (0.45^{*}) and seed numbers (0.54^{**}) had highly significant positive relationships with N application rates in 2013. The close relationships between N supply and crop morphological traits or yield components across years provided experimental evidence on how weather variations could determine the responses of canola crop to N application.

The grain yield of canola is a function of plant density, number of pods per plant, number of seeds per pod, and the seed weight (Ma et al. 2015). Many studies have found that a high rate

of N application generally increases number of branches, number of pods and overall crop assimilation, and thus contributes to increased grain yield (Rose et al. 2008; Ozer 2003). Yield components are often compensated from each other, and responses of yield components to N application are largely influenced by some other factors, including weather, cultivar, soil type, residual fertility, soil moisture content, and other factors (Holmes and Ainsley 1977). Therefore, yield components do not always exhibit a consistent response to the amounts of N application, especially in large field studies.

Effects of nitrogen application rates on grain yield of canola

The responses of grain yield to different rates of N applications in all three years are presented in Table 3, Figures 3 and 4. In 2012, grain yields of the N treated strips varied from 2201 to 2330 kg ha⁻¹, or an increment of 6.8, 12.6 and 6.3% for 50 kg ha⁻¹ N, 100 kg ha⁻¹ N and 150 kg ha⁻¹ N treatments, respectively, compared with the unfertilized control field-strips (mean of 2070 kg ha⁻¹). However, significant increase in grain yield (13%) was found only in the 100 kg ha⁻¹ N treated (2330 kg ha⁻¹) field-strips, i.e. 2.6 kg ha⁻¹ yield increment for each additional kg N ha⁻¹. No significantly different yields were found among the field-strips that received different N treatments (Table 3).

In 2013, grain yields of N treated strips were significantly greater for 50 kg ha⁻¹ N, 100 kg ha⁻¹ N and 150 kg ha⁻¹ N treatments (means of 2748, 2854 and 2803 kg ha⁻¹), than the control (mean of 1847 kg ha⁻¹), or increased by 49, 55 and 52%, respectively. Again, increasing N applications from 50 to 150 kg ha⁻¹ did not result in any significant increase in yield.

In 2014, although all rates of N treated strips had numerically higher grain yields than grain yield in the control strips, there were no statistically significant differences among the four N treatments.

Overall in this study, all N treatments showed numerically higher grain yield values in all three years, compared to the grain yield in the control strips (Table 3, Fig. 4). These increases were statistically significant in 2012 (100 kg N ha^{-1}) and in 2013 with all three N treatments (Table 3). However, the higher N rates did not achieve consistently higher yield increments and the treatment of 100 kg N ha^{-1} fertilizer was likely the optimum to produce the highest grain yield in 2012 and 2013. The large spatial variation in yield potential across the field is shown in Figure 3, where it indicated that grain yields were significantly different among field-strips that received the same N treatment. For example, in the control field-strips in 2012, and in the 50 kg ha^{-1} N treated field-strips in both 2012 and 2013, significantly different grain yields were observed among the replicates that received the same N treatment.

Relationship between soil mineral nitrogen and crop measurements and grain yields

Since plant available N pool is represented by SMN contents, the associations between crop growth parameters and SMN levels are useful for assessing the potential for in-season N management decisions of canola. In this study, plant height was positively correlated with SMN contents measured at all three growth stages in all three years. However, statistically significant positive relationship was found only at all three stages of cropping in 2012 (0.45^* , 0.78^{***} and 0.39^* for preplant, early flowering and post-harvest, respectively), and at early flowering stage in 2013 (0.58^{***}). In addition, in both years, the strongest relationship between plant height and SMN contents was found with SMN measured at early flowering stage (0.78^{***} in 2012 and

0.58*** in 2013). LAI at the early flowering also had a positive correlation with SMN measured at preplant (0.68* in 2012) and early flowering stages (0.74** in 2012 and 0.73*** in 2013). Although plant biomass production had a positive correlation with SMN contents measured at all three growth stages (with few exceptions), significantly positive correlation was found only at the early flowering stage in 2013 (0.41*).

Some of the yield components also showed positive linear relationships with the SMN contents, and others were not correlated well with the SMN contents (Table 5). For example, branch number was positively correlated with SMN contents at all three stages, with a strong relationship found only at the early flowering stage (0.46* in 2013).

In this study, SMN contents measured at the early flowering stage in 2013 showed a significant positive relationship with grain yield (0.40*). There were also weak positive relationships between SMN contents measured at different growth stages and grain yields of canola in all three years (except preplant SMN in 2012 and early flowering SMN in 2014). Overall, these results show that SMN at early flowering stage is well correlated with most of the crop growth parameters (plant height and LAI in both 2012 and 2013, and aboveground plant biomass in 2013), yield components (number of branches per plant in 2013) and grain yields (2013) of canola. Such correlations indicate the potential of some crop parameters and SMN measured at early flowering stage could be used as indicators for guiding in-season variable rate N applications.

In this study in all three years, yield data showed positive relationships with most of the crop parameters (Table 5). However significantly positive relationships were found only with the number of pods per plant in both 2012 and 2013 ($R^2 = 0.46^*$ and 0.49^{**} , respectively), with plant height (0.42*) and number of branches per plant (0.45*) in 2013. The weak relationships

between grain yield and yield components were probably due to the effect of large spatial variability in this large canola field, or partly due to the varying weather conditions across the years, which exerted a larger impact on yield formation than the effect of N nutrition.

Conclusions

This study examined the spatial variability and dynamic responses of SMN, crop growth measurements, and yields of canola to different rates of preplant N applications. Both SMN contents and grain yield varied significantly across field-strips that received different N treatments and within field-strips that received the same N treatment, indicating a substantial spatial variability in soil N supply power. Some crop measurements (LAI, aboveground plant biomass, and number of branches, pods per plant and plant density) varied widely across the field-strips, while other crop measurements (plant height, number of plants, pods and seeds) varied even within the field-strip that received the same N treatment, or within the unfertilized control field-strips. In general, the close correlations between SMN and plant height or between SMN and LAI measured at early flowering stage suggest good potential of using these parameters for in-season variable rate N application for canola crop production. The inconsistent responses of grain yield of canola crop to preplant fertilizer N application was likely due to the influence of large spatial variability of the field. Overall, strong associations between SMN contents and crop parameters measured at early flowering stage, and grain yield provide substantial evidence for in-season variable rate N application for canola crop production in northern Ontario.

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Table 1. Soil (0-30 cm) characteristics at preplant, field operation and growing season conditions in an on-farm canola experiment conducted at Verner, ON for all three years.

	2012	2013	2014
<u>Soil characteristics</u>			
Soil Type	Clay to clay loam	Loam to silt loam	Loam to silt loam
Soil Texture:			
Clay (g kg^{-1})	222	216	213
Silt (g kg^{-1})	564	461	478
Sand (g kg^{-1})	213	323	321
Soil pH (1:1 with water)	6.4	7.5	6.6
Organic Matter (g kg^{-1})	37	-	-
Sodium bicarbonate soil test P ($\mu\text{g g}^{-1}$)	86	12.5	114
Mineral N ($\text{NH}_4^+ + \text{NO}_3^-$) ($\mu\text{g g}^{-1}$)	9.1	5.4	7.8
Ammonium acetate soil test K ($\mu\text{g g}^{-1}$)	133	110	127.7
<u>Field operations</u>			
Date of seeding	May 5	May 15	May 30
Planting depth (cm)	0.6-1.2	0.6-1.2	0.6-1.2
Seeding rate (kg ha^{-1})	5.6	5.6	5.6
Stand count (plants m^{-2}) at rosette stage (GS 30-32) ^y	53	50	62
Row spacing (cm)	20	20	20
Date of harvesting	August 29	September 18	August 26 ^z
<u>Growing season conditions</u>			
Mean temperature ($^{\circ}\text{C}$)	16.8	14.9	15.0
Growing degree-days from planting to harvest (base temperature of 0°C)	2096	1978	1510
Growing season total rainfall (mm)	449	508	521
May	51	102	88
June	90	56	68
July	60	129	85
August	146	96	182

September

102

125

98

^y GS 30-32 refers to the growth stage code using the BBCH scale (Lancashire et al. 1991).^z date of hand harvest.

For Review Only

Table 2. Descriptive statistics of responses of soil mineral N (SMN) contents ($\mu\text{g g}^{-1}$) to different rates of preplant N applications in all three years.

Year	N Rate	Preplant					Early flowering					Post-harvest				
		Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%
2012	0N	8.4 <i>a</i>	5.2	11.8	2.3	27.1	12.3 <i>c</i>	8.4	15.8	2.8	22.7	8.7 <i>b</i>	5.2	12.0	2.3	27.0
	50N	8.9 <i>a</i>	6.1	12.2	1.7	19.3	24.1 <i>b</i>	18.6	29.1	4.2	17.4	11.6 <i>b</i>	9.2	15.9	2.1	18.2
	100N	8.9 <i>a</i>	5.4	12.0	1.9	21.8	27.7 <i>b</i>	21.5	38.1	5.3	19.1	10.6 <i>b</i>	7.5	14.3	3.0	28.5
	150N	9.7 <i>a</i>	6.5	13.5	2.0	20.4	37.5 <i>a</i>	30.3	52.8	9.4	25.1	20.6 <i>a</i>	7.3	41.8	11.9	57.5
2013	0N	5.5 <i>a</i>	4.8	6.3	0.6	11.5	5.3 <i>b</i>	4.3	6.4	0.7	13.5	–	–	–	–	–
	50N	5.3 <i>a</i>	3.8	8.1	1.5	28.0	13.1 <i>b</i>	8.4	25.6	6.0	46.0	–	–	–	–	–
	100N	5.3 <i>a</i>	3.7	9.1	1.9	35.1	20.4 <i>b</i>	13.4	38.3	8.6	42.4	–	–	–	–	–
	150N	5.4 <i>a</i>	4.5	6.4	0.6	12.0	38.6 <i>a</i>	19.0	69.8	18.7	48.3	–	–	–	–	–
2014	0N	7.0 <i>a</i>	4.9	9.6	1.7	24.6	17.0 <i>a</i>	14.8	19.0	1.4	8.3	–	–	–	–	–
	50N	9.2 <i>a</i>	5.8	13.1	2.9	31.5	22.5 <i>a</i>	12.3	32.1	7.3	32.3	–	–	–	–	–
	100N	7.3 <i>a</i>	4.5	12.4	3.0	42.0	23.1 <i>a</i>	7.6	32.0	8.4	36.3	–	–	–	–	–
	150N	7.6 <i>a</i>	5.1	11.7	2.5	32.9	25.0 <i>a</i>	14.0	40.1	9.5	38.0	–	–	–	–	–

Note: Means with different letters in the same year are significantly different at the significance level of 0.05.

Table 3: Descriptive statistics of crop growth parameters of canola measured at early flowering and grain yield in all three years

Year	N Rate	Plant height (cm)					LAI					Biomass (kg ha ⁻¹)					Grain yield (kg ha ⁻¹)				
		Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%
2012	0N	123.8c	114.90	131.9	7.01	5.7	0.6b	0.31	0.89	0.29	47.3	391.7a	289.9	496.3	71.0	18.1	2070b	1707	2317	261	12.6
	50N	136.9b	125.30	151.8	8.59	6.3	1.1b	0.93	1.2	0.14	12.9	420.6a	316.2	646.2	117.4	27.9	2210ab	1692	2550	309	14.0
	100N	143.3b	134.60	161	8.52	6.0	0.8b	0.59	0.95	0.18	23.8	513.1a	402.8	709.7	98.4	19.2	2330a	2138	2533	147	6.3
	150N	159.0a	151.10	167	6.04	3.8	2.5a	1.6	3.3	0.87	35.3	478.7a	397.9	556.3	55.4	11.6	2201ab	2005	2361	153	6.9
2013	0N	113.9c	94.1	136.4	15.0	13.2	1.3b	0.86	2.0	0.40	29.6	215.7c	78.0	320	78.5	36.4	1847b	1227	2107	301	16.3
	50N	120.5b	113	127.9	5.0	4.1	2.3b	1.5	3.0	0.56	24.4	303.3bc	193.0	510	114.5	37.8	2748a	2436	3118	260	9.4
	100N	125.9b	107.5	142.2	11.8	9.4	2.4b	1.1	4.0	1.03	43.0	354.4b	216.0	562	120.4	34.0	2854a	2623	3021	157	5.5
	150N	141.6a	132.3	152.5	7.6	5.4	3.5a	2.6	4.3	0.62	17.8	438.6a	230.0	690	129.3	29.5	2803a	2487	3098	226	8.1
2014	0N	129.5b	117	140.2	8.67	6.7	1.4b	1.1	1.8	0.32	22.9	181.2a	137.7	224.8	34.4	19.0	2331a	1905	3260	487	20.9
	50N	143a	129.8	155	10.25	7.2	2.1a	0.88	2.9	0.78	36.6	253.6a	180.1	360.8	60.3	23.8	3712a	2553	6204	1311	35.3
	100N	148.7a	145.4	153.8	2.87	1.9	2.0ab	1.2	2.8	0.55	26.8	246.9a	168.5	313.3	48.8	19.8	3539a	2489	4715	800	22.6
	150N	146.5a	127.6	162.8	13.81	9.4	2.0ab	1.1	2.7	0.54	26.7	199.6a	109.4	230.2	46.5	23.3	2988a	2717	3324	274	9.2

Note: Means with different letters in the same year are significantly different at the significance level of 0.05.

Table 4: Descriptive statistics of yield parameters of canola measured shortly after the physiological maturity stage in all three years

Year	N	Branches plant ⁻¹					Pods plant ⁻¹					Seeds pod ⁻¹					Plant density (Plants m ⁻²)				
		Mean	Min	Max	Stdev	CV %	Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%	Mean	Min	Max	Stdev	CV%
2012	0N	3.3 <i>b</i>	2.1	3.9	0.74	22.6	112.0 <i>a</i>	66.8	148.8	28.4	25.5	22.6 <i>b</i>	20.2	25.0	2.0	8.8	89 <i>a</i>	65	150	29.5	33.0
	50N	4.2 <i>a</i>	2.7	6.6	1.19	28.4	138.0 <i>a</i>	91.8	188.2	37.4	27.1	23.9 <i>ab</i>	21.6	26.5	1.4	5.7	63 <i>b</i>	45	85	15.1	23.9
	100N	3.8 <i>ab</i>	2.8	4.44	0.62	16.3	137.0 <i>a</i>	117.4	177.8	21.6	15.8	25.1 <i>a</i>	23.0	30.1	2.4	9.6	74 <i>a</i>	45	110	21.6	29.1
	150N	4.4 <i>a</i>	3.5	6.20	1.00	22.8	129.0 <i>a</i>	51.4	192.8	47.2	36.5	23.9 <i>ab</i>	18.8	28.8	3.1	12.9	81 <i>a</i>	55	120	22.8	28.3
2013	0N	1.8 <i>c</i>	0.8	2.8	0.8	42.8	42.0 <i>b</i>	22.1	66.0	15.7	37.3	20.4 <i>a</i>	18.3	21.7	1.2	6.0	125 <i>a</i>	65	180	41.5	33.2
	50N	2.7 <i>b</i>	1.8	3.8	0.7	25.4	48.0 <i>ab</i>	34.0	58.3	9.7	20.1	21.7 <i>a</i>	20.0	25.7	1.8	8.5	85 <i>a</i>	75	110	11.5	13.6
	100N	2.5 <i>b</i>	1.8	3.2	0.5	21.2	74.3 <i>a</i>	42.4	118.4	23.1	31.1	22.0 <i>a</i>	21.0	23.7	1.1	5.2	98 <i>a</i>	60	180	41.5	42.4
	150N	4.1 <i>a</i>	2.8	5.8	1.1	26.5	63.2 <i>ab</i>	32.5	103.4	24.6	39.0	23.0 <i>a</i>	20.5	25.3	1.7	7.2	105 <i>a</i>	60	190	39.5	37.6
2014	0N	6.3 <i>a</i>	4.4	8.4	1.6	25.7	122.0 <i>a</i>	92.6	146.4	23.4	19.2	–	–	–	–	–	93 <i>a</i>	73	123	21.9	23.5
	50N	8.4 <i>a</i>	4.0	11.6	3.5	41.8	162.0 <i>a</i>	81.8	235.0	53.6	33.1	–	–	–	–	–	92 <i>a</i>	75	108	12.6	13.8
	100N	6.8 <i>a</i>	5.0	9.6	1.5	22.4	154.1 <i>a</i>	95.8	227.8	43.6	28.3	–	–	–	–	–	76 <i>a</i>	65	85	8.2	10.7
	150N	7.0 <i>a</i>	3.8	12.4	3.1	44.3	147.9 <i>a</i>	91.2	237.0	53.2	35.9	–	–	–	–	–	85 <i>a</i>	70	113	14.8	17.4

Note: Means with different letters in the same year are significantly different at the significance level of 0.05.

Table 5. Pearson correlation coefficients of soil mineral N contents, crop growth parameters, yield components and grain yields of canola.

Year		Yield	Height	LAI ^z	Biomass	Branch	Pods	Plants	Seeds	Min.N _{PP}	Min.N _{EF}	Min.N _{PH}
2012	Min.N _{PP}	0.26	0.45*	0.68*	0.08	0.25	0.17	-0.0003	-0.01	1		
	Min.N _{EF}	0.19	0.78***	0.74**	0.36	0.32	0.02	-0.08	0.29	0.43*	1	
	Min.N _{PH}	0.11	0.39*	0.33	0.20	0.18	0.01	-0.12	0.04	0.35	0.35	1
	N rate	0.24	0.85***	0.70*	0.41*	0.33	0.17	-0.06	0.24	0.44*	0.82***	0.52**
	Yield	1	0.27	0.35	0.19	0.15	0.46*	-0.22	0.31			
	N uptake	0.23	0.73***	0.69*	0.22	0.17	0.01	0.19	0.07	0.57**	0.72***	0.44*
2013	Min.N _{PP}	-0.17	0.19	0.21	0.03	0.02	0.07	-0.14	0.19	1		n/a
	Min.N _{EF}	0.40*	0.58***	0.73***	0.41*	0.46*	0.31	0.05	0.32	-0.25	1	n/a
	N rate	0.70***	0.71***	0.74***	0.61**	0.56**	0.45*	-0.14	0.54**	-0.07	0.75***	n/a
	Yield	1	0.42*	0.44*	0.53**	0.45*	0.49**	-0.43*	0.36	-0.17	0.40*	n/a
2014	Min.N _{PP}	0.26	0.17	-0.17	0.16	-0.36	-0.32	0.18	n/a	1		n/a
	Min.N _{EF}	-0.37	0.25	0.14	0.24	0.001	0.03	-0.07	n/a	-0.01	1	n/a
	N rate	0.26	0.55*	0.58**	0.51*	0.03	0.18	-0.03	n/a	-0.005	0.37	n/a
	Yield	1	0.05			0.25	.038	-0.05	n/a	0.26	-0.37	n/a

Note: *, **, *** Significant at the significance level of 0.05, 0.01 and 0.001, respectively.

^z LAI measured at the early flowering stage while all the other crop parameters determined at final harvest. Min.N_{PP}, Min.N_{EF} and Min.N_{PH} stand for Mineral N at preplant, early flowering and at post-harvest stage, respectively.

Figure captions:

Figure 1. Spatial variation of soil mineral N (kg ha^{-1}) among the field-strips that received the same nitrogen treatment (replicates) in relation to different rates of nitrogen fertilizer application. Means with different letters in the same year are significantly different at the 0.05 probability level.

Figure 2. Spatial variation of soil mineral nitrogen levels as indicated by standard deviation (PP, EF and PH are referring preplant, early flowering and post-harvest, respectively) in relation to different nitrogen rates.

Figure 3. Spatial variation of grain yield of canola (kg ha^{-1}) in all three years in relation to different rates of N fertilizer application among the field-strips (replicates). Means with different letters in the same year are significantly different at the 0.05 probability level.

Figure 4. Canola grain yield response to different rates of preplant N applications in large field-strips experiment in all three years.

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