Main factors affecting nutrient and water use efficiencies in spring canola in North America: a review of literature and analysis

Dilumi W. K. Liyanage, Manjula S. Bandara, and Michele N. Konschuh

*Department of Biological Sciences, University of Lethbridge, Lethbridge, T1K 3M4, AB, Canada; *MCB Agric-Research Consulting, Brooks, AB, Canada

Corresponding author: Michele N. Konschuh (email: m.konschuh@uleth.ca)

Abstract

Improving nutrient and water use efficiencies by optimizing field management practices are important strategies to increase economic and environmental sustainability of canola production in North America. The objective of this study was to review recent research publications and quantitatively assess the impact of field management practices on the efficiency of water and selected macronutrients [nitrogen (N) and sulfur (S)] in canola and to identify the most effective cultural practices for improved efficiencies. The results showed that, overall, the addition of N and S inputs in studies across North America increased yield but had a negative impact on nitrogen use efficiency (NUE) and sulfur use efficiency (SUE) compared with corresponding controls. Split-applied N in spring can improve NUE, but these improvements are mostly dependent on the soil moisture content. SUE is improved when N is supplied to complement the S application. Sulfate forms of S are more readily available and should be applied early in the season, whereas elemental S must be applied in the fall to improve SUE. Maintenance of adequate soil moisture conditions during the reproductive phase of the canola crop improves water use efficiency (WUE). Supplementary irrigation improves SUE, but most canola crops are grown under rain-fed conditions in North America. Maintaining tall stubble until spring and then incorporating it with N improved WUE in canola. In summary, our analyses suggest that further research is required on the integration of canola genotypes with improved nutrient and water use efficiencies and effective management.

Key words: Brassica napus, Brassica campestris, nitrogen, sulfur, irrigation

Résumé

Pour rendre la culture du canola plus durable sur les plans de l’économie et de l’environnement en Amérique du Nord, il importe d’améliorer l’efficacité avec laquelle la plante utilise l’eau et les oligoéléments par l’agronomie. Les auteurs ont dépouillé les articles scientifiques récemment publiés et évalué quantitativement l’impact des pratiques agronomiques associées à une meilleure utilisation de l’eau et de certains macronutriments (en l’occurrence l’azote et le soufre) pour cerner les méthodes culturales qui accroissent le rendement. Dans l’ensemble, en Amérique du Nord, l’addition d’azote et de soufre relève le rendement, mais nuit à une assimilation efficace de ces deux éléments, comparativement aux témoins correspondants. L’application fractionnée d’un engrais azoté au printemps améliore l’assimilation de l’azote. Cependant, les améliorations notées dépendent surtout de la teneur en eau du sol. Ajouter de l’azote à l’engrais soufré rehausse l’assimilation du soufre, qui est mieux assimilé sous forme de sulfate. Celui-ci devrait être appliqué au début de la période végétative alors que le soufre élémentaire devrait l’être à l’automne, en vue d’une meilleure utilisation. Une teneur en eau suffisante pendant la période reproductrice améliorera l’absorption d’eau par le canola. Un apport d’eau supplémentaire sous forme d’irrigation accroîtra l’efficacité avec laquelle la culture utilise l’eau, mais, en Amérique du Nord, on produit surtout du canola sous régime pluvial. Laisser un chaume élevé jusqu’au printemps, puis l’incorporer au sol avec un engrais azoté améliorera l’efficacité avec laquelle le canola utilise l’eau. En résumé, ces analyses laissent croire qu’il faudrait entreprendre d’autres recherches afin d’intégrer le génotype aux études sur une gestion efficace et une meilleure assimilation des oligoéléments et de l’eau par le canola. [Traduit par la Rédaction]

Mots-clés : Brassica napus, Brassica campestris, azote, soufre, irrigation
Introduction

Canola (Brassica napus L. and Brassica campestris L.) is the second largest field crop grown in Canada, with 8.4 million ha seeded in 2020, and 99.4% of the total production is confined to the Canadian Prairies (https://www150.statcan.gc.ca/n1/daily-quotidien/190626/dq190626b-eng.htm). The USDA National Agricultural Statistics Service estimated that about 0.81 million ha of canola was seeded in the USA in 2019 with an average productivity of 4000 kg ha⁻¹.

Since the inception of the Green Revolution, there has been a significant increase in the use of inputs in agricultural food production systems worldwide, particularly nitrogen (N) fertilizer (Hartmann et al. 2015; Lu and Tian 2017). It has been projected that the global human population will reach 9.7 billion by 2050 (United Nations 2019); hence, food production and distribution will be a crucial challenge for feeding the predicted population. The global utilization of synthetic N fertilizer in 1961 was 11.3 Tg N (Lu and Tian 2017), and the demand in 2020 increased to 108.7 Tg N (FAO 2019), which is a 9.6-fold increase over the past six decades. Although N fertilizer is known to increase seed yields of various crop species (Heisey and Mwangi 1996; Hawkesford 2014; Ngezimana and Agenbag 2014), excessive N application has produced adverse effects on crop, soil, environment, and ground water quality (Ladha et al. 2005; Hartmann et al. 2015; Cui et al. 2018; Liang et al. 2018; Zhang et al. 2018). Nitrogen use efficiency (NUE) typically declines with progressively increasing N supply, which is an outcome of nutrient responses that follow Mitscherlich’s law of diminishing returns in agricultural systems. The concept of 4R Nutrient Stewardship introduced by Fertilizer Canada and others (Fertilizer Canada 2021) encourages producers to consider the right source of N, the right rate of application, the right timing of application, and the right place to apply N. A balance between N input to obtain crop yield and NUE must be maintained for sustainable crop production (Chen et al. 2014; Zhang et al. 2016; Cui et al. 2018; Ding et al. 2018).

NUE may have different definitions, but it is commonly defined as seed yield that is produced per unit of available N, including soil test and applied N (Gan et al. 2008). Determination of NUE is an important approach to evaluate the fate of applied N fertilizers and their role in enhancing canola yield and minimizing production costs (Ma and Herath 2016). Due to the high demand for N, high rates of N fertilizer are commonly applied to canola to achieve maximum seed yields (Balint and Rengel 2008). Canola has relatively low NUE because of poor N utilization in tissues rather than low efficiency in N uptake from soil. Poor N utilization in tissues results in a low N harvest index mainly through seed sink limitations (relatively low yield potential and small seed harvest index) and partially due to the fall of N-rich leaves (Svecnjak and Rengel 2006). Thus, fine-tuned N nutrition together with the identification of cultivars with enhanced nitrogen utilization efficiency (NUE) is of commercial interest due to better use of N fertilizers and may increase crop yield (Balint and Rengel 2008). Improving NUE of canola is important in the development of sustainable agricultural systems to optimize crop productivity in an economically and environmentally responsible manner (Bouchet et al. 2016; Ma and Herath 2016).

Important factors that affect NUE in a crop production system include weather, water availability, tillage practices, residue retention, crop rotation, fertilizer rate, timing, placement, and source (Maaz et al. 2016). Crop input usage is also influenced by crop species and efficiency, input prices, perceptions, and growers’ attitudes towards innovation and risk.

Canola requires higher amounts of N than wheat and barley (Grant and Bailey 1993; Brennan et al. 2000; Brennan and Bolland 2009). As a non-legume oilseed crop, canola also has a higher demand for N fertilizer per unit seed yield than other oilseed crops (Balint and Rengel 2008; Bouchet et al. 2016). Most prairie soils are deficient in plant-available N, thus nitrogen fertilizers are required to increase canola yields (Grant and Bailey 1993), and N accounts for the highest energy use and input cost in oilseed cultivation systems (Gan et al. 2008; Ma and Herath 2016; Ma et al. 2019). Many studies in western Canada have focused on the seed yield response of Argentine canola (B. napus) and canola-quality B. campestris cultivars to N fertilizer (Racz et al. 1965; Ridley 1972; Henry and MacDonald 1978; Nuttall et al. 1987; Bailey 1990) and have shown a significant increase in yield and (or) economic returns from applied N, depending on growing conditions and the level of soil test NO₃-N (Soper et al. 1971; Nyborg et al. 1999). Although B. campestris cultivars generally have lower yield potential than B. napus cultivars, breeding efforts have significantly improved the agronomic traits and yield of new cultivars, particularly hybrids, compared with those grown earlier (Saskatchewan Agriculture and Food 2000). As an increased supply of nutrients is typically required to support higher yields, fertilizer rates and other crop management practices may need to be re-evaluated to ensure that the improved genetic potential is consistently realized. This also suggests the possible need for separate management recommendations for specific canola cultivars.

Although selecting new crop cultivars and identifying the optimum N application rate are being used to improve NUE in wheat, barley, and canola (Gan et al. 2008; Malhi et al. 2010; Hawkesford 2014; Hartmann et al. 2015; Smith et al. 2019), field management practices for better N utilization must also be developed, as crop management practices can affect NUE differently among crop species, including canola and wheat (Malhi et al. 2006). Applying N fertilizer in excess of what the canola crop requires can be harmful because this encourages lodging, reduces seed yield and seed quality by decreasing oil content and increasing chlorophyll content of the seed, and increases production costs (Ma et al. 2019). Excess N application reduces NUE, increases production costs, and increases the vulnerability of fertilizer loss during the growing season via volatilization, denitrification, surface run-off, leaching, and stabilization into soil organic matter by clay colloids, and consequently increases N losses from the agro-ecosystem (Heaney et al. 1992; Nyborg et al. 1997; Raun and Johnson 1999; Brennan et al. 2000; Karamanos et al. 2003; Rathke et al. 2005; Wu et al. 2016, 2018; Ma et al. 2019). Nitrogen losses can occur with increasing N supply as crop plants approach physiological inefficiencies of N use (Gan et al. 2008). Ma and Herath (2016) identified that expansion of canola production in eastern Canada is highly dependent on the development of
regional or site-specific guidelines for environmentally sound N management that focus on improving NUE as a result of these risks. Maaz et al. (2016) reported that environmental conditions, such as weather and water availability, and cultural practices, such as tillage, residue retention, crop rotation, and fertilizer rate, timing, placement, and N source are the most influential factors that affect NUE in crop production systems.

Sulfur (S) is an essential component of the amino acids, cysteine, and methionine in plants, and the Brassicaceae family generally requires larger amounts of S than wheat and barley (Nuttall et al. 1987; Grant and Bailey 1993) to synthesize sulfur-containing secondary metabolites called glucosinolates (Haneklaus et al. 2007). In many areas, where canola is grown, S deficiencies can be observed (Grant et al. 2012). In Canada, most canola crops are grown in the parkland region of the three prairie provinces (Statistics Canada 2011) and more than four million ha of agricultural soils in those regions are deficient or potentially deficient in plant available S for high seed yield of canola (Grant et al. 2012). Sulfur deficiency is greatly affected by soil characteristics. In soils that are low in organic matter, S release by mineralization is limited, and in coarse-textured soils, S has leached out from the rooting zone over time (Franzen and Grant 2008). The risk of S deficiency decreases with higher organic matter content and higher potential mineralization as sulfate is released slowly from organic matter. In Canada, S deficiencies were identified on the Gray Luvisolic soils, because they are highly leached soils with a low organic matter content. Sulfur deficiencies have been identified in a broad range of soils in North America with the increased production of canola, use of higher yielding cultivars, movement to more intensive crop production systems, and decrease in aerial deposition of S due to increased air quality standards. Sulfur application can also influence canola quality. Under S-deficient conditions, the concentration of oil in canola increased with S application (Grant et al. 2012). In addition, the application of S with N in S-deficient soil has been reported to increase seed protein content (Malhi 2006; Malhi and Gill 2007; Egesel et al. 2009). In contrast, some studies reported a reduction in protein content with S application, which can be attributed to dilution from an increased seed yield response when a severe S deficiency was corrected (Malhi and Gill 2002; Grant et al. 2003a).

Hammac et al. (2017) found that water and temperature variability played a larger role than soil nutrient status, particularly N and S on canola seed yield in Northwest USA. While access to irrigation has increased crop productivity in soil moisture deficit semi-arid regions in the Canadian Prairies for decades, water scarcity and escalating costs of investing in and managing the infrastructure could hinder further expansion of irrigation. Subsequently, there is a need for new approaches for agriculture to keep pace with the rising demand for food and fibre while applying the lowest possible amounts of irrigation. To achieve better use of water, the production of dry matter or marketable crop must be increased per unit of water used in evapotranspiration and for irrigation in semi-arid and desert areas (Viet 1962). Crop water productivity also known as water use efficiency (WUE) refers to a given level of biomass or seed yield per unit of water used by the crop (Hatfield et al. 2001). WUE depends on inherent crop productivity, growing conditions (particularly amounts of sunshine and effects of atmospheric temperature and humidity), and harvest index (Aiken et al. 2011). Water utilization of a crop is primarily affected by its canopy and weather conditions under an adequate soil water supply (Suyker and Verma 2010). These effects are represented by seasonal crop coefficients and the potential evaporative demand of the atmosphere. The crop coefficient refers to the fraction of potential evapotranspiration (ET) that the crop is expected to use on a given day. The crop coefficient value varies with the crop stage (Aiken et al. 2011).

WUE has been defined in other ways as well. Earlier, WUE was defined as the amount of carbon assimilated or crop yield per unit of transpiration (Viet 1962) and later as the amount of abovebiomass or marketable yield per unit of evapotranspiration. Irrigation scientists describe WUE as a ratio of total supplied water transpired to water diverted from the source, whereas crop researchers define it as the ratio of total biomass/grain yield to water supplied (Israelsen 1932; Sharma et al. 2015). The authors of the publications reviewed for this manuscript defined the WUE as the ratio of seed yield produced to the total amount of water available to the crop (rainfall and irrigation water).

In their review and interpretation, Assefa et al. (2018) summarized the major factors determining spring and winter canola yield in North America and subjected some of these factors to a meta-analysis. They identified rainfall/irrigation, latitude/radiation, soil properties/soil nutrient/fertilizer, temperature, and length of growing season as the factors with the greatest impact on canola yield. The only other meta-analyses found for canola in our review of recent literature focused on canola oil or meal in human and animal feeding studies.

The objectives of this study were to (i) assess the effect of fertilizer inputs (N and S), applied as single or combination treatments, irrigation, and indirect soil moisture management (stubble management and tillage) on the nutrient and water use efficiencies of canola; (ii) understand the influence of field management practices on these nutrients and water use efficiencies, (iii) provide recommendations for future research, and (iv) identify suitable strategies to improve canola production efficiency in North America.

Materials and methods

Data search and collection

Recent peer-reviewed publications were compiled by searching Google Scholar and the University of Lethbridge Library database by using the following keywords: “canola”, “North America”, “NUE”, “WUE”, “water”, “nitrogen”, “sulfur”, “irrigation”, and “seed yield”. To avoid any bias, previous publications were selected according to the following criteria: (i) the field experiment must have been conducted in North America; (ii) the cropping system in the field experiment must contain spring Argentine canola; (iii) the study included one or more of the following management-related factors: N fertilizer rates, S fertilizer rates, irrigation, or soil moisture management; (iv) studies reported seed yields; (v)
treatments must have been replicated and randomized; and (vi) if one study reported different years or site-year observations within the same experiment, each year or site-year observations were considered as separate observations (Van Groenigen et al. 2013). Accordingly, a total of 24 publications were incorporated into our dataset. The dataset consisted of 355 measurements for NUE from 12 peer-reviewed publications from 2008 to 2020, 276 measurements for SUE from 4 peer-reviewed publications from 2002 to 2020 and 99 measurements for WUE from 8 peer-reviewed publications from 2004 to 2020. The research locations included in this review are shown in Fig. 1. Soil information and weather data from these locations are provided in Table S1.

**Data processing**

NUE was calculated as

\[
\text{NUE} = \frac{Y}{N}
\]

(1) where NUE is the nitrogen use efficiency (kg kg\(^{-1}\)), \(Y\) is the crop yield (kg ha\(^{-1}\)), and \(N\) is the amount of N (kg N ha\(^{-1}\)) applied as fertilizer.

WUE was calculated as

\[
\text{WUE} = \frac{Y}{W}
\]

(2) where WUE is the water use efficiency (kg mm\(^{-1}\)), \(Y\) is the crop yield (kg ha\(^{-1}\)), and \(W\) is the total amount of irrigation water plus rainfall (mm), representing total water input.

SUE was calculated as

\[
\text{SUE} = \frac{Y}{S}
\]

(3) where SUE is the sulfur use efficiency (kg kg\(^{-1}\)), \(Y\) is the crop yield (kg ha\(^{-1}\)), and \(S\) is the amount of S available in soil plus S applied as fertilizer (kg S ha\(^{-1}\)).

NUE values were analyzed in the following categories: source of N (urea vs. controlled-release urea (CRU)), application (urea spring band vs. combinations of N source) (CRU and a blended mixture) and timing (spring-banded, fall-banded, and split application), N rate, species (\(B.\ napus\) vs. other species) × N rate, year × N rate, variety × N rate, S rate × N rate, stubble management (stubble retained or incorporated) × N rate, and fertigation stage (no fertigation vs. other).

WUE values were grouped into nine categories: irrigation at different growth stages (rain-fed vs. partially or fully irrigated), stubble height (no stubble at seeding vs. stubble maintained at different heights and seeding), irrigation rate (rain-fed vs. different amounts of irrigation), time of stubble management (no stubble in spring vs. stubble at different heights either in spring or fall), irrigation (rain-fed vs. irrigated), row spacing × stubble height (30 cm apart with 15 cm stubble height vs. wider spacings with taller (>15 cm) stubble heights), species × water regime (\(B.\ napus\) vs. well-watered vs. other species, rain-fed or no precipitation), species × seeding date (\(B.\ napus\) seeded early spring vs. \(B.\ napus/\ B.\ campestris\) seeded late spring or late fall), and species × stubble management (\(B.\ napus\) on fallow vs. \(B.\ napus\) on stubble or \(B.\ campestris\) on fallow or stubble).

SUE values were grouped into four categories: N rate × S rate, application timing-growth stage × S rate (incorporated at seeding vs. side-banded and seed row placed at seeding and top-dressed or foliar applied at bolting and early flowering), S rate (no S applied vs. different rates of S applied), and timing × source × S rate (spring-applied ammonium sulfate at 10 kg S ha\(^{-1}\) vs. spring/fall-applied S in various fertilizer forms applied at two rates (10 or 20 kg S ha\(^{-1}\)).

**Results and discussion**

Rates of N fertilizer application and NUE

Brassica oilseed crops respond to N fertilizer positively even if applied at rates as high as 180 kg N ha\(^{-1}\), but the amount of N fertilizer required for maximum yield of oilseed species differs, depending on environmental conditions (Brandt et al. 2002; Gan et al. 2008). Assefa et al. (2018) also concluded that canola yield plateaus when available N reaches 100 to 200 kg ha\(^{-1}\), depending on the environment. Ma and Zheng (2016) suggested that the optimum rate of N fertilizer for canola production is ~150 kg ha\(^{-1}\) in humid regions, such as eastern Canada and higher yield and (or) NUE and can be obtained when N fertilizer is side-dressed, under normal weather conditions. Lafond et al. (2008) reported that in the western Canadian prairies, applying 50% of N in-season can efficiently match N requirements and reduce the risk of N leaching (Ma and Zheng 2016). This suggests that N application rates may not yet be optimized for canola production.

A field study conducted at 11 sites in Saskatchewan from 2003 to 2005 showed that there was a general trend of decreasing NUE with increasing N fertilizer rate in all five of the oilseed species studied, including \(B.\ napus\) (Gan et al. 2008). Maximum NUE was obtained at N fertilizer rates up to 100 kg N ha\(^{-1}\) less than the rates required to maximize seed yield (130 kg N ha\(^{-1}\)). Gan et al. (2008) reported that at any given fertilizer rate, NUE was high when soil N supply was low, although the trend for NUE and fertilizer NUE was similar. Furthermore, the study reported that the magnitude of decrease in NUE with increasing rates of N fertilizer was interactively influenced by soil N supply and rainfall during the months of vigorous vegetative growth and flowering period (June and July). The crop N uptake response to fertilizer varied among oilseed species; however, all oilseed species showed a similar N uptake response at sites with low (100 mm) rainfall in these months (Gan et al. 2008). Under high rainfall (250 mm) conditions, \(r.\ apia\) canola was the poorest user of fertilizer and soil N, while \(j.\ canol\)a canola and mustard were better at using N under higher moisture conditions (Gan et al. 2008). Therefore, Gan et al. (2008) recommended optimizing rates of N fertilizer for different canola species under different environmental conditions, soil N supply, and rainfall to improve NUE in canola production.
Timing, source, and placement of N fertilizer application and NUE

Optimization of the timing of N applications is a must for developing best nutrient management practices to improve NUE (Ma and Zheng 2016). Canola yield is associated with growing-season dry matter (DM) accumulation (Karamanos et al. 2005). In a canola crop, the greatest DM accumulation can be seen during the flowering period. In addition, the effect of N fertilizer on canola yield partially depends on the capacity of the crop to mobilize N from senescing vegetative organs to seeds. The seed yield and the DM content could be affected by the timing of N application, however contradictory results were reported (Ma and Zheng 2016). A study under humid eastern Canadian conditions indicated that side dressed N application at the 6-leaf stage is more effective in improving crop N uptake and provides better N economy in comparison with an equal amount of N received entirely at the preplant stage. Therefore, split application is more productive because it provides N at suitable stages during crop growth (Ma and Herath 2016). Ma and Herath (2016) also reported that the rates and timing of fertilizer N required to maximize the yield of canola depend on environmental conditions. In contrast, studies conducted in western Canada under arid and semi-arid conditions by Grant et al. (2012) showed that split applications of N were no more effective in both DM and yield than all N applied at seeding, likely as a result of different soil moisture conditions. Therefore, a better understanding of the underlying changes in seasonal DM and N accumulation and utilization in seed formation may be necessary to improve both the seed yields and NUE (Ma and Zheng 2016).

An N source-placement study conducted by Malhi et al. (2010) included two sources of N (urea and controlled release urea; CRU) applied alone and in combination in a blend, and different placement methods (spring-banded, fall-banded, or split application (half of fertilizer spring banded and half broadcasted at tillering)). Spring banding CRU improved NUE compared with spring-banded urea applications, but only marginally. Their results also showed that fall-applied urea produced the lowest NUE (19.4 kg kg\(^{-1}\) N), and spring-banded CRU produced the highest (24.5 kg kg\(^{-1}\) N) NUE, with a narrow range. In general, irrespective of the difference in N source, spring-applied N treatments had higher NUE than the fall-applied N. This may be due to volatilization, immobilization or leaching of CRU under warm fall conditions or early spring weather conditions. The authors concluded that for boreal soils of the Canadian prairies, spring-banded CRU is as effective as urea, and in some years more effective, in increasing crop yield and N recovery. The study showed that urea/CRU blends and split applications of urea had similar NUE to that of spring-banded CRU (Malhi et al. 2010). Split applications have the advantage of providing an available source of N early in the season and reducing the risk of N losses (Malhi et al. 2010).
Water supply and NUE

The canola crop root system has a high surface area characterized by long root hairs, which play an important role in nutrient acquisition and transport in water-limited soils (Pan et al. 2016). For instance, dry spring conditions can leave soil N “stranded” due to impaired root growth, thus restricting available N uptake (Pan et al. 2007). Previous studies showed that water supply during the flowering period is critical for oilseed production as low soil moisture content during this crop growth stage can negatively impact plant N uptake, thus reducing the photosynthetic activity of leaves and mobilization of the assimilate (Morrison and Stewart 2002; Gan et al. 2004, 2008). Another study showed that, with increasing available water and fertilization, spring canola becomes more efficient at accumulating both grain mass per unit grain N and grain N per unit of available N supply (NUE) (Maaz et al. 2016). In addition, NUE component analysis indicated that water-enhanced yields were correlated with higher N uptake and utilization efficiencies, which in turn were attributed to higher grain NUE, followed by higher N retention. Most canola production occurs in arid and semi-arid regions where irrigation infrastructure is absent, therefore, canola cultivars should be screened for improving WUE and grain N accumulation in environments with limited water supply (Maaz et al. 2016).

Except for one study conducted by Smith et al. (2019), the NUE studies that we considered in our analysis did not include irrigation treatments, where the water deficit conditions would be minimized. However, in some studies, stubble management treatments were included in combination with N rate with the objective of conserving available soil water to support the crop productivity and improve the NUE. No positive impact on NUE was reported in the studies that were considered, and soil water deficit conditions may have played an important role in the mediocre response to N treatments.

Genotypic variation and NUE

Genotypic variation in NUE has been reported among oilseed canola cultivars, which suggests that uptake and distribution of N in canola is an inherited characteristic. Significant genotypic variations in yield under N limiting conditions and in yield responses to high inputs of fertilizer N were reported for spring canola. Furthermore, it was indicated that the genotypic differences in NUE are more apparent under limited N than under optimum N supply. The yield response of canola cultivars under limited N level may depend partially on their inherent ability to remobilize N from senescing leaves and translocate them to developing seeds (Svečnjak and Rengel 2006). In addition, the extensiveness of the canola root system correlates with genotypic variation in NUE (Maaz et al. 2016). A previous study reported that the N uptake efficiency (NUE) of canola seed is predominantly determined by root growth instead of the N uptake rate per unit of root surface (Kamh et al. 2005). Several studies have indicated the genetic diversity of N-related traits in both spring and winter cultivars under field and controlled conditions (Svečnjak and Rengel 2006; Kessel et al. 2012; Ulas et al. 2013; Lee et al. 2015). Combining the genetic diversity of the spring and winter gene pools using backcrosses may enhance genetic variation for NUE improvement (Bouchet et al. 2016). Moreover, genetic variation in the activity of different nitrate and ammonium transporters could be relevant to improve NUpE in canola (Xu et al. 2012).

Sulfur use efficiency of canola

Canola is sensitive to S concentrations in plant tissue, as S is an essential component of amino acids, cysteine and methionine, and oilseed crops in the Brassicaceae family contain high levels of sulfur-containing secondary metabolites, called glucosinolates. Canola requires about four times more S than wheat or maize, and an adequate supply of S is important for optimum growth and yield (Haneklaus et al. 2007; Abdallah et al. 2010). In canola, a low S supply suppresses the development of reproductive organs and leads to silique abortion, decreased seed yield, and decreased oil content (Ngezimana and Agenbag 2014). Therefore, oilseed crops have a greater demand for S compared with cereal crops (Haneklaus et al. 2007). Field trials carried out over the years across the Canadian prairies determined that in canola, optimum yield can be achieved at rates of application of 15-30 kg S ha⁻¹ (Malhi and Gill 2006, 2007; Karamanos et al. 2007; Malhi et al. 2007).

Both N and S are important constituents of protein and adequate supplies of both nutrients are required to optimize crop yield (Grant et al. 2012). Inadequate S combined with an excessive amount of N can lead to a nutrient imbalance that can restrict protein synthesis and reduce canola growth and yield (Malhi and Gill 2002). The interactive effects of N and S on canola yields have demonstrated that N fertilizers stimulate plant S uptake and yield responses to applied S only occurred when N was applied (Ngezimana and Agenbag 2014). Therefore, N and S additions must be in balance for optimum crop yield (Jackson 2000; Malhi et al. 2007; Malhi and Gill 2007). In western Canada, it is recommended that S be applied in a fertilizer mixture having an N to S ratio of 5:1 to 7:1 (Karamanos et al. 2007).

In contrast, field crops in eastern Canada were rarely fertilized with S as anthropogenic sources of S from airborne pollution (acid rain) and inherent soil S reserves have historically been considered sufficient to meet crop S requirements (Ma et al. 2019). Environment Canada measured SO₄-S deposition levels ranging from 5.6 to 11.2 kg S ha⁻¹ in 1990, but only approximately 3.4 kg S ha⁻¹ in recent years (OMAFRA 2018). Consistent with this diminished S availability, Ma et al. (2019) reported that fertilizer S application greatly improved canola seed yields at 6 out of 9 site-years, and the highest NUE was observed in the N150 + S20 kg ha⁻¹ treatment, suggesting the importance of S supplement when high N rates are applied for canola production in eastern Canada.

Sulfur fertilizer source, and timing and method of application

Various S-containing fertilizers are utilized, including gypsum (CaSO₄·2 H₂O) and potassium sulfate (K₂SO₄), but in the northern great plains, the most widely used S sources are ammonium sulfate ((NH₄)₂SO₄), ammonium thiosulfate
eral, the soilson the semi-arid Canadian prairies do not reach sufficient available S to optimize yields of the oxidation rate of S is simply not rapid enough to release is mediated by soil microorganisms. In many environments, applications of sulfate forms of S, however, are vulnerable to leaching losses under high moisture conditions in sandy soils thereby reducing fertilizer use efficiency (Malhi 1998, 2005; Grant et al. 2004; Malhi et al. 2009).

Elemental S fertilizers must be oxidized to the sulfate form before they are available for crop uptake, and the oxidation is mediated by soil microorganisms. In many environments, the oxidation rate of S is simply not rapid enough to release sufficient available S to optimize yields of Brassica species in the year of application, or possibly for several years. In general, the soils on the semi-arid Canadian prairies do not reach temperatures above 10 °C until mid-May and microbially mediated S oxidation may be slow due unfavourable soil conditions resulting in reduced availability of SO4-S to the respective crops (Malhi and Leach 2003; Wen et al. 2003; Grant et al. 2004; Karamanos and Poisson 2004). This may explain the poor or negative response to elemental S by the canola crop.

Malhi and Leach (2003) showed that applying a higher rate of elemental S sometimes increased SUE, and more importantly, that SUE for elemental S improved significantly when elemental S was fall applied compared with spring applied. In fact, the SUE of fall-applied elemental S came closer to that observed with spring applied sulfate-S products (Malhi and Leach 2003). Elemental S should be managed in a manner that increases particle dispersion and contact with the soil microorganisms to accelerate the oxidation process (Grant et al. 2012). Recent work with micronized elemental sulfur shows potential for use with canola (Bremer et al. 2021).

Canola has a high demand for S during flowering and seed set stages (Malhi et al. 2007). If deficiencies are observed during the growing season, application of S source as late as rosette to early bolting can be beneficial. However, yield will generally be lower than if the S had been available from the start of crop growth (Grant et al. 2012). Malhi and Gill (2002) applied sulfur as potassium sulfate at different stages of growth either as a top-dressed treatment or as a foliar application. Their results showed that the response to S and SUE was greatest when applied at seeding, followed by bolting, followed by flowering and foliar applications that were better than top-dressed applications at some sites. In addition, ammonium sulfate and ammonium thiosulfate may have residual benefits on S availability for several years after application, depending on the environmental conditions. For example, in the Canadian prairies under low leaching conditions, applications of 20–30 kg S ha\(^{-1}\) as ammonium sulfate reduced S deficiency in crops for 2–4 years after application (Grant et al. 2003b, 2004; Malhi and Leach 2003; Karamanos and Poisson 2004). Residual benefits from sulfate fertilizers may be due to carry over of SO4-S as ammonium sulfate has been shown to enhance soil SO4-S (Malhi et al. 2009).

Under adequate soil moisture conditions, a range of application methods can be used to supply readily available S for plant growth and the response to the method of placement for S source varies with the soil and weather conditions. In a study conducted in the black and gray soils of the northern Canadian prairies, similar canola yields were obtained by applying ammonium sulfate as a surface broadcast, in-soil banded or seed-placed, under reduced or conventional tillage (Grant et al. 2004). However, a 3-year study conducted in northern Saskatchewan reported a higher seed yield with placement of ammonium sulfate in the seed row and (or) side-banded compared with broadcast and incorporated S in one year, while in the remaining two years all treatments had comparable yields (Malhi and Gill 2002). This may have occurred because the S bands were better accessed by the roots under drier conditions compared with the shallow placement in surface soil.

Genotypic variation and SUE Most of the canola currently produced is from hybrid cultivars that have a higher yield potential compared with open-pollinated cultivars (Carew and Smith 2006). Previous studies conducted across western Canada indicated that, hybrid cultivars produced higher yields at a given S level than did open-pollinated cultivars (Karamanos et al. 2005; Brandt et al. 2007). That is, the optimum yield can be achieved with S levels similar to those required to achieve sub-optimal yield of open-pollinated cultivars, showing that the hybrid cultivars may be better able than the open-pollinated cultivars to extract S from the soil (Karamanos et al. 2005, 2007; Malhi and Gill 2006).

Effect of field management practices on SUE Our analysis shows that adjusting the N rate with the S rate resulted in a higher SUE compared with other management practices, such as only adjusting S rate, applying S in spring or fall, and applying S at different growth stages either as a top-dressed or foliar treatment. An N rate × S rate study was conducted in eastern Canada, where soil moisture was not as limiting a factor as in the Canadian prairies. This multiple-year (2012–2014) study composed of 12 treatment combinations with three levels of S (0, 20, and 40 kg ha\(^{-1}\)) and four levels of N (50, 100, 150 and 200 kg N ha\(^{-1}\)) rates. The results showed that the growing season had a significant effect on the SUE of different treatments (Ma et al. 2020). These results indicate that the effect on SUE among years was not consistent when applied N rates were considered; however, it confirmed that the highest SUE rate corresponded with 20 kg ha\(^{-1}\) for a given level of N and additional S did not always improve SUE. The lowest SUE was noted from a 3-year (2000–2002) study that included two rates of S (20 and 40 kg S ha\(^{-1}\)) applied in fall or spring using elemental S and SO4-S as sources. As expected, the results suggested that S applied in the sulfate form produced a higher SUE than the treatments with elemental S in all years (Malhi and Leach 2003).
Improving WUE of canola

In the Brown and Dark Brown soil zones, which comprise most of the semi-arid Northern Great Plains, the potential evaporative demand for water usually exceeds the water available to the crop, representing the greatest limitation to crop production in this semi-arid region (Cutforth et al. 2002). Therefore, improving WUE, especially in the drier regions of the prairies, is an important consideration for increasing yield (Hu et al. 2015). In the present analysis, the impacts of several factors, including canola species, seeding date, irrigation and irrigation timing, stubble height, and timing of stubble incorporation, on the WUE of canola were considered.

Canola has a deep taproot system, and it can extract water from a soil depth down to 1.7 m (Din et al. 2011; Zhu et al. 2016). Out of total soil water extraction, canola can withdraw 45% of water from below 0.6 m (0.6–1.7 m) depth. Also, the short growing season of canola further reduces its irrigation requirement (Katuwal et al. 2020).

Oilseed yield is expected to increase with water use, up to a maximum yield potential (Anastasi et al. 2010). The rate of yield increase, relative to increased water use, represents a measure of water productivity.

One of the greatest challenges for agriculture is to develop technology or agronomic approaches to improve WUE. WUE is partially a function of canola adaptation to environmental conditions. Therefore, favourable agronomic approaches are of great importance. Canola has been shown to have WUE values ranging from 8.3 to 11.4 kg ha⁻¹ mm⁻¹ in the sub-humid regions of Canada (Faraji et al. 2009). The growing season on the Canadian prairies generally extends from May to August with most of the precipitation during June and July. After seeding, canola emerges, normally in May, and then grows rapidly through June and early July. The rapid increase in leaf surface area, along with high temperature can increase evapotranspiration and create a moisture deficit during the growing season. A moisture deficit can arise depending on the amount of spring soil moisture and the local level of precipitation, and under limited soil moisture, the crop can be harmed due to water stress during growth and development (Bullock et al. 2010). In addition, canola prefers cooler temperatures, especially during the flowering period and high temperatures during the flowering stage can also lead to a reduction in yield (Cardillo et al. 2015). The effect of irrigation rate and the ability to irrigate (rain-fed vs. irrigated) improved WUE in a positive way, but these practices are not available to all producers. In years with insufficient rainfall, yield increased with irrigation treatments and WUE increased as well (Hergert et al. 2016). In years with adequate rainfall, improvements in yield and WUE between treatments were not always evident.

Irrigation was compared with that of rain-fed canola production by Katuwal et al. (2020). Treatments that provided irrigation from emergence to harvest had the highest WUE followed by full season irrigation (seeding to harvest), whereas withholding irrigation at the reproductive stage resulted in the poorest WUE (Katuwal et al. 2020). These results confirm that a satisfactory supply of water at the reproductive stage of canola is key for improved WUE. As the overall above-ground biomass and leaf area index reach a peak during the reproductive stage (Katuwal et al. 2018), it likely increases total water loss through surface transpiration and increases ET in canola. In addition to the increased ET requirement, the reproductive stage is characterized by many water-sensitive processes such as floral retention, floral bud development into pods and assimilate supply from leaves and pods for seed setting which determines yield in oilseed crops (Eck et al. 1987; Sweeney et al. 2003; Katuwal et al. 2020). Katuwal et al. (2020) reported that skipping irrigation during the vegetative stages and irrigating only during the reproductive stage could maximize water productivity without significantly changing seed yield in canola.

Angadi et al. (2004) measured WUE in relation to canola seeding date. They reported that early spring seeding resulted in greater WUE than early fall planting, which was better than late spring planting with both Brassica rapa and B. napus. The canopy of spring canola is established under cool conditions with modest evaporative demand. Therefore, evaporative losses can somewhat be avoided. Aiken et al. (2011), stated that delaying initial irrigation can reduce evaporation from the soil surface before canopy closure and increase the crop transpiration fraction of ET. Deficit irrigation is a method of utilizing limited irrigation water resources, in which crops are supplied with water below their evapotranspiration requirements during less critical growth stages (Yang et al. 2017). A previous study conducted in the US Southern Great Plains showed that adopting spring canola cultivar L140 and skipping irrigation during the vegetative stage (seeding to bolting) could enhance WUE in water-limited semi-arid regions like the US Southern Great Plains (Katuwal et al. 2020). The WUE of spring canola can be enhanced by minimizing evaporative losses from soil by delaying initial irrigation, seeking rapid canopy closure, or planting an early spring oilseed that forms the canopy under conditions of low evaporative demand. In addition, increasing harvest index can improve WUE and this can be favoured by planting optimal populations, selecting appropriate planting dates, varieties, or hybrids, and avoiding water deficits for vigorous growth and during floral development and seed fill. Furthermore, developing varieties and hybrids that maintain crop productivity and yield under soil water deficit conditions can increase WUE.

The second most effective practice for improving WUE was maintaining stubble height of the crop preceding the canola crop after harvest. This research consisted of leaving wheat stubble standing at various heights, including extra tall (45 cm), tall (30 cm), and short (15 cm) heights from the soil surface. The effect of the stubble height on WUE was compared with that of no stubble (cultivated after harvest). The results suggested that, in general, compared with cultivated stubble, the tallest stubble (45 cm) had the highest WUE followed by 30 and 15 cm standing stubble (Cutforth et al. 2011). Cardillo et al. (2015) reported that, depending on stubble height, stubble management changed the micro-climate near the soil surface by reducing wind speed, solar radiation, and soil temperatures throughout the life cycle of canola. Tall stubble was found to reduce wind speed, soil drying, and evapotranspiration compared with shorter stubble (Cardillo et al. 2015). Their results suggest that tall stubble may have in-
increased seed yield and WUE by providing a favourable microclimate for increased water conservation. The treatment with no stubble had the lowest WUE. Combining row spacing with stubble height did not have a large impact on WUE.

The third most effective practice for improving WUE was the time of stubble incorporation, which included stubble maintained at 30 cm in fall and seeded to canola in spring, stubble maintained at 15 cm or 30 cm in height and seeded to canola in spring, cultivation in fall and seeded to canola in spring, stubble maintained at 30 cm and seeded to canola with an extra 34 kg N ha⁻¹ added in spring, and stubble cut at 30 cm tall in fall and then cultivated in spring and seeded to canola. Among these treatments, stubble maintained at 30 cm with extra N produced the highest WUE compared with stubble cut at 30 cm tall in fall then cultivated in spring and seeded, suggesting that both soil moisture and added N had a synergistic positive effect on plant growth and yield, resulting in an improved WUE (Cutforth et al. 2006). These results agree with those of Miller et al. (2003) and Cutforth et al. (2002), who reported that canola and mustard grown in the semi-arid prairie can respond to higher levels of N under favourable moisture conditions. In spite of the potential to conserve soil moisture, the positive response of canola varied with the species studied. A study by Angadi et al. (2008) reported a negative impact on WUE from planting into stubble, and this was attributed mainly to the poor yield response to any stubble by both B. napus and B. campestris, compared with fallow (Angadi et al. 2008). Angadi et al. (2008) also showed that WUE for B. rapa was greater than for B. napus under drought conditions, but that B. napus WUE was higher under rain-fed and irrigated conditions.

Summary and conclusion

Economically and environmentally sustainable food production is essential to meet global demands as the human population continues to increase. While genetic improvement for enhanced productivity of the world’s most dominant food and fibre crops is in progress, the adoption of appropriate crop management practices to utilize production inputs, particularly N and water, effectively will be key to reaching the genetic potential and economic sustainability of those field crops.

Canola is the second largest field crop grown in Canada, and a significant and expanding oilseed crop in the Northern Great Plains and Pacific Northwest region in the USA. No meta-analyses were found for crop inputs on canola, although one review by Assefa et al. (2018) summarized the major management factors determining the productivity of spring and winter canola in North America.

For our analysis, we collected 730 measurements associated with “factors affecting water and selected plant nutrients, N- and S-use efficiency in canola” conducted in North America (Canada and the USA). The dataset consisted of 355 measurements for NUE from 12 peer-reviewed publications from 2008 to 2020, 276 measurements for SUE from 4 peer-reviewed publications from 2002 to 2020, and 99 measurements for WUE from 8 peer-reviewed publications from 2004 to 2020. The available data were used to analyze the effect of different field management practices, such as nutrient (N and S) applications, as single or combined sources of the nutrients, irrigation, tillage, and stubble management on the NUE, SUE and WUE of canola. The objective was to understand the influence of field management practices on nutrients and water use efficiencies and to identify suitable strategies to improve canola production in North America.

Overall, the results of our analysis show that, in most cases, the addition of N and S fertilizers across North America had a positive effect on yield, but a negative impact on NUE and SUE as compared with the corresponding controls. This was mainly due to the diminishing nature of productivity with an increasing rate of applied plant nutrients. Furthermore, almost all the agronomic approaches used to increase yield resulted in a negative impact on NUE. The use of higher rates of N under poor soil moisture conditions could create an adverse growing environment for the crop (additive or synergistic effect of salinity and drought), lowering both the productivity and NUE.

In canola, NUE was occasionally improved with spring applications. Spring-banded CRU was as effective as urea and sometimes more effective, increasing crop yield and recovery. Split applications have the advantage of providing N early in the season with the option to add additional N if adequate moisture is available, thus reducing the potential for N losses. The positive, but marginal, effect of the split-applied control-release N source (urea) on NUE in canola suggests that for improved NUE, integrated management practices, including appropriate N source and method of application, need to be further evaluated.

Application of S in combination with N was shown to increase SUE. Sulfate forms of S are more readily available to the plant than elemental S, but are also more vulnerable to losses. Spring applications of SO₄-S are better than fall applications, and earlier applications improved SUE compared with applications later in the season. Applying S in bands was shown to improve SUE under drier conditions, but not under adequate soil moisture conditions. Foliar applications were often more effective than soil applications. Fall applications of elemental S improved SUE compared with spring applications because there is more time for elemental S to oxidize to SO₄-S when applied in the fall. The interactive effects of N and S on canola yields have been demonstrated, with a conclusion that N fertilizers encourage S uptake, and that N and S applications must be in balance to achieve optimum seed yields of canola grown in S-deficient soils.

Among the various approaches aimed at improving WUE in canola, several management practices, namely, irrigation during the reproductive stage, maintaining tall stubble, and incorporating stubble in spring rather than fall, had a positive impact on WUE. Irrigation maintained from seedling emergence to physiological maturity resulted in the greatest WUE followed by full season irrigation (seeding to harvest), whereas withholding irrigation during the reproductive stage resulted in the lowest WUE confirming that adequate soil moisture is critical during the reproductive stage for improved yield and WUE in canola.

As in most other field crops, satisfactory soil moisture is crucial for high yields of canola. Therefore, for greater WUE,
maintenance of adequate soil moisture conditions from flowing until physiological maturity through supplementary irrigation and (or) maintaining stubble height is critical. Finally, there has been limited attention or focus on the assessment of canola species and cultivars for improved NUE, SUE, and WUE. There is reported genetic variation in N uptake in spring and winter type canola that has not yet been fully exploited. Some canola hybrids also appear to have greater SUE than open pollinated varieties. The WUE for B. rapa was greater than that for B. napus in drought situations, and B. napus WUE was higher than B. rapa WUE in rain-fed and irrigated situations. There is a need for the new canola cultivars to be further evaluated on a regional basis for their nutrient and water use efficiencies to ensure economic sustainability for this crop in North America.

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Author information
Author notes
Manjula S. Bandara is retired.

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References
Abdallah, M., Dubouset, L., Meuriot, F., Etienne, P., Avice, J. C., and Ourry, A. 2010. Effect of mineral sulfur availability on nitrogen and sulfur uptake and remobilization during the vegetative growth of

Brassica napus L. Exp. Bot. 61: 2635–2646. doi:10.1093/jxb/erq096. PMID: 20403880.

Aiken, R., Lamm, F., Aboukheir, A. A., and Wolfe, D. 2011. Water use of oilseed crops. In Proceedings of the 23rd Annual Central Plains Irrigation Conference, Burlington, CO, 22–23 February 2011. pp. 181–189.

Anastasi, U., Santonoceto, C., Guiñfré, A. M., Sortino, O., Gresta, F., and Abbate, V. 2010. Yield performance and grain lipid composition of standard and oleic sunflower as affected by water supply. Field Crops Res. 119: 145–153. doi:10.1016/j.fcr.2010.07.001.

Angadi, S. V., Cutforth, H. W., McConkey, B. G., and Gan, Y. 2004. Early seeding improves the sustainability of canola and mustard production on the Canadian semiarid prairie. Can. J. Plant Sci. 84: 705–711. doi:10.4141/P03-140.

Angadi, S. V., McConkey, B. G., Cutforth, H. W., Miller, P. R., Ulrich, D., Selles, F., et al. 2008. Adaptation of alternative pulse and oilseed crops to the semiarid Canadian prairie: seed yield and water use efficiency. Can. J. Plant Sci. 88: 425–438. doi:10.4141/CJPS07078.

Assefa, Y., Prasad, P. V., Foster, C., Wright, Y., Young, S., Bradley, P., et al. 2018. Major management factors determining spring and winter canola yield in North America. Crop Sci. 58: 1–16. doi:10.2135/cropsci2017.02.0079.

Bailey, L. D. 1990. The effects of 2-chloro-6-(trichloromethyl)-pyridine (‘N-serve’) and N fertilizers on productivity and quality of Canadian oilseed rape. Can. J. Plant Sci. 70: 979–986. doi:10.4141/cjps90-120.

Balint, T., and Rengel, Z. 2008. Nitrogen efficiency of canola genotypes varies between vegetative stage and grain maturity. Euphytica, 164: 421–432. doi:10.1007/s10681-008-9693-6.

Bouchet, A. S., Laperche, A., Bissuel-Belaygue, C., Snowdon, R., Nesi, N., and Stahl, A. 2016. Nitrogen use efficiency in rapeseed. A review. Agron. Sustain. Dev. 6: 1–20.

Brandt, S. A., Ulrich, D., Lafond, G., Malhi, S. S., and Johnston, A. M. 2002. Management for optimum yield of open pollinated and hybrid canola. In Soils and Crops Workshop. Available from http://hdl.handle.net/10388/9763 [accessed 30 November 2020].

Brandt, S. A., Malhi, S. S., Ulrich, D., Lafond, G. P., Kutcher, H. R., and Johnston, A. M. 2007. Seeding rate, fertilizer level and disease management effects on hybrid versus open pollinated canola (Brassica napus L.). Can. J. Plant Sci. 87: 255–266. doi:10.4141/P05-223.

Bremer, E., Pauly, D., Strandhord, S. M., and McKenzie, R. H. 2021. Evaluation of a sprayable elemental sulfur fertilizer under field conditions in Alberta. Can. J. Soil Sci. 101: 216–221. doi:10.1139/cjss2020-0134.

Brennan, R. F., and Bolland, M. D. A. 2009. Comparing the nitrogen and phosphorus requirements of canola and wheat for grain yield and quality. Crop Pasture Sci. 60: 566–577. doi:10.1071/CP08401.

Brennan, R. F., Mason, M. G., and Walton, G. H. 2006. Assessing the contribution of genetic enhancements and fertilizer application regimes on canola yield and production risk in Manitoba. Can. J. Agric. Econ. 54: 215–226. doi:10.1111/j.1744-7976.2006.00046.x.

Cardillo, M. J., Bullock, P., Guldner, R., Glenn, A., and Cutforth, H. 2015. Stubble management effects on canola performance across different climatic regions of Western Canada. Can. J. Plant Sci. 95: 149–159. doi:10.4141/cjps-2014-172.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., et al. 2014. Producing more grain with lower environmental costs. Nature, 514: 486–489. doi:10.1038/nature13609. PMID: 25186728.

Cui, Z., Zhang, H., Chen, X., Zhang, C., and Ma, W. C. L. H. 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature, 555: 363–366. doi:10.1038/nature25785. PMID: 29513654.

Cutforth, H. A., McConkey, B., Angadi, S., and Judiesch, D. 2011. Extra-tall stubble can increase crop yield in the semiarid Canadian prairie. Can. J. Plant Sci. 91: 783–785. doi:10.4141/cjps10168.
Ma, B. L., and Zheng, Z. M. 2016. Relationship between plant nitrogen and phosphorus accumulations in a canola crop as affected by nitrogen management under ample phosphorus supply conditions. Can. J. Plant Sci. 96: 853–866. doi:10.1139/cjps-2015-0374.

Ma, B. L., Zheng, Z., Whalen, J. K., Calderwood, C., Vanasse, A., Pageau, D., et al. 2019. Uptake and nutrient balance of nitrogen, sulfur, and boron for optimal canola production in eastern Canada. J. Plant Nutr. Soil Sci. 182: 252–264. doi:10.1002/jpl.2070615.

Malhi, S. S., Laidlaw, J. W., Solberg, E. D., and Malhi, S. S. 1997. Denitrification and nitrous oxide emissions from a black chernozem soil during spring thaw in Alberta. Can. J. Soil Sci. 77: 153–160.

Malhi, S. S., Leach, D. 2003. Effectiveness of elemental S fertilizers on canola after four annual applications. In Soils and Crops Work-shop. Available from http://hdl.handle.net/10388/10013 [accessed 30 November 2020].

Malhi, S. S., and Gill, K. S. 2006. Cultivar and fertilizer S rate interaction effects on canola yield, seed quality and S uptake. Can. J. Plant Sci. 86: 91–98. doi:10.4101/P05-058.

Malhi, S. S., and Gill, K. S. 2007. Interactive effects of N and S fertilizers on canola yield and seed quality on S-deficient gray luvisol soils in northeastern Saskatchewan. Can. J. Plant Sci. 87: 211–222. doi:10.4101/P05-218.

Malhi, S. S., and Leach, D. 2003. Effectiveness of elemental S fertilizers on canola after four annual applications. In Soils and Crops Workshop. Available from http://hdl.handle.net/10388/10013 [accessed 30 November 2020].

Malhi, S. S., Lemke, R., Wang, Z. H., and Chabra, B. S. 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. Soil Tillage Res. 90: 171–183. doi:10.1016/j.still.2005.09.001.

Malhi, S. S., Can, Y., and Rancy, J. P. 2007. Yield, seed quality, and sulfur uptake of Brassica oilseed crops in response to sulfur fertilization. Agron. J. 99: 570–577. doi:10.2134/agronj2006.0269.

Malhi, S. S., Schoenau, J. J., and Vera, C. L. 2009. Influence of six successive annual applications of sulphur fertilizers on wheat in a wheat-canola rotation on a sulphur-deficient soil. Can. J. Plant Sci. 89: 629–644. doi:10.4101/CJPS08217.

Malhi, S. S., Soon, Y. K., Grant, C. A., Lemke, R., and Lupwayi, N. 2010. Influence of controlled-release urea on seed yield and N content, and N use efficiency of small grain crops grown on Dark Gray Luvisols. Can. J. Soil Sci. 90: 363–372. doi:10.4101/CJSS90102.

Miller, P. R., Can, Y., McConkey, B. G., and McDonald, C. L. I. 2003. Pulse crops for the northern great plains. II. Cropping sequence effects on cereal, oilseed, and pulse crops. Agron. J. 95: 980–986.

Morrison, M. J., and Stewart, D. W. 2002. Heat stress during flowering in cereal, oilseed, and pulse crops. Agron. J. 94: 399–412. doi:10.2134/agronj2001.00021962005700040007x.

Ngezimana, W., and Agenbag, G. A. 2014. The effect of nitrogen and sulphur on yield and seed quality of oilseed rape (Brassica napus L.) grown in different growth stages for yield, seed quality and S uptake of canola. Can. J. Plant Sci. 86: 665–674. doi:10.4101/P01-184.

Racz, G. J., Webber, M. D., Soper, R. J., and Hedlin, R. A. 1965. Phosphorus and nitrogen utilization by rape, flax, and wheat. Agron. J. 57: 335–337. doi:10.2134/agronj1965.0002196200700040007x.

Soomer, R. J., Racz, G. J., and Fehr, P. I. 1971. Nitrate nitrogen in the soil as a means of predicting the fertilizer nitrogen requirements of barley. Can. J. Soil Sci. 51: 45–49. doi:10.4141/cjss71-006.

Statistics Canada. 2011. Field and special crops (Seeded area). Ottawa, Statistics Canada. Available from http://www40.statcan.gc.ca/l01/cst01/prim11a-eng.htm [accessed 2020/01/6].

Suyker, A. E., and Verma, S. B. 2010. Coupling of carbon dioxide and water vapor exchanges of irrigated and rainfed maize-soybean cropping systems and water productivity. Agric. For. Meteorol. 150: 553–563. doi:10.1016/j.agrformet.2010.01.020.

Svecnjak, Z., and Rengel, Z. 2006. Nitrogen utilization efficiency in canola cultivars at grain harvest. Plant Soil, 283: 299–307. doi:10.1007/s11104-006-0022-5.

Sweeney, D. W., Long, J. H., and Kirkham, M. B. 2003. A single irrigation to improve early maturing soybean yield and quality. Soil Sci. Soc. Am. J. 67: 235–240. doi:10.2136/sssaj2003.2350.

Uljas, A., Behrens, T., Wiesler, F., and Horst, W. J. 2013. Does genotypic variation in nitrogen remobilisation efficiency contribute to nitrogen efficiency of winter oilseed-rape cultivars (Brassica napus L.)? Plant Soil, 371: 463–471. doi:10.1007/s11104-013-1688-y.

United Nations. 2019. World population prospects. Available from http://www.un.org/desa/population/publications/wpp/ [accessed 1 January 2021].

Van Groenigen, K. J., Van Kessel, C., and Hungate, B. A. 2013. Increased greenhouse-gas intensity of rice production under future atmospheric conditions. Nat. Climate Change, 3: 288–291. doi:10.1038/nclimate1712.

Viet, F. G. 1962. Fertiliser and efficient use of water. Adv. Agron. 14: 223–264. doi:10.2307/2311508.

Veten, G., Schoenau, J. J., Moeleki, S. P., Inanaga, S., Yamamoto, T., Hama-ro, M., et al. 2020. Graphical analysis of nitrogen and sulfur supply on yield and N and N fertilizer as a means of predicting the fertilizer nitrogen requirements of barley. Can. J. Soil Sci. 99: 536–545. doi:10.1139/cjss-2018-0287.

Wen, G., Schoenau, J. J., Mooreli, S. P., Inanaga, S., Yamamoto, T., Hamaro, M., et al. 2020. Effectiveness of an elemental sulfur fertilizer in an oilseed-cereal-legume rotation on the Canadian prairies. J. Plant Nutr. Soil Sci. 166: 54–60. doi:10.1002/jpl.203900012.
Wu, L., Liu, X., and Ma, X. Y. 2016. Spatio-temporal variation of erosion-type non-point source pollution in a small watershed of hilly and gully region, Chinese Loess Plateau. Environ. Sci. Pollut. Res. Int. 23: 10957–10967. doi:10.1007/s11356-016-6312-2.

Wu, L., Peng, M., Qiao, S., and Ma, X. 2018. Assessing impacts of rainfall intensity and slope on dissolved and adsorbed nitrogen loss under bare loessial soil by simulated rainfalls. Catena, 170: 51–63. doi:10.1016/j.catena.2018.06.007.

Xu, G., Fan, X., and Miller, A. J. 2012. Plant nitrogen assimilation and use efficiency. Annu. Rev. Plant Biol. 63: 153–182. doi:10.1146/annurev-arplant-042811-105532. PMID: 22224450.

Yang, H., Du, T., Qiu, R., Chen, J., Wang, F., Li, Y., et al. 2017. Improved water use efficiency and fruit quality of greenhouse crops under regulated deficit irrigation in northwest China. Agric. Water Manag. 179: 193–204. doi:10.1016/j.agwat.2016.05.029.

Zhang, Y., Wu, J., and Xu, B. 2018. Human health risk assessment of groundwater nitrogen pollution in Jinghui canal irrigation area of the loess region, northwest China. Environ. Earth Sci. 77: 273.10.1007/s12665-018-7456-9.

Zheng, W., Zhang, M., Liu, Z., Zhou, H., Lu, H., Zhang, W., et al. 2016. Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system. Field Crops Res. 197: 52–62. doi:10.1016/j.fcr.2016.08.004.

Zhu, M., Monroe, J. G., Suhail, Y., Villiers, F., Mullen, J., Pater, D., et al. 2016. Molecular and systems approaches towards drought-tolerant canola crops. New Phytol. 210: 1169–1189. doi:10.1111/nph.13866.