Canola (*Brassica napus* L. cv. ‘Canola’) is a rapeseed cultivar with edible oil quality. Rapeseed is the second largest oil crop produced around the globe at 36 million ha (FAO, 2014). The rapeseed crop is also the second largest global source of protein meal for animal rations (USDA-ERS, 2012). In addition to the protein, rapeseed is the third most produced vegetable oil after soybean (*Glycine max* (L.) Merr.) and oil palm (*Elaeis guineensis* Jacq.) (Downey and Rimmer, 1993). Rapeseed is originally from Asia and the Mediterranean, with natural oil quality often used industrially due to its high erucic acid. Canadian plant breeders, however, identified a rapeseed with both low erucic acid (<2%) and glucosinolate (<30 μmol g⁻¹) content in its defatted meal (Mag, 1983; Lin et al., 2013) and called it canola (to mean Canada oil or Canada oil with low acid).

Canola is a cool-season broadleaf crop that has both winter and spring varieties. Canola varieties that should be planted and establish in the fall season (usually between August and November), overwinter, and resume growth in spring are referred as winter canola varieties. Canola varieties that can be planted in spring (usually after March) and that do not need to overwinter are referred as spring canola varieties. As a cool-season crop, canola has demonstrated itself as an alternative rotation crop to spring and winter grasses such as wheat (*Triticum aestivum* L.) (Bushong et al., 2012). As a broadleaf, it allows for better weed control via

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**ABSTRACT**

Canola (*Brassica napus* L. cv. ‘Canola’) production has both economic and agronomic advantages. The objectives of this review were to summarize the key management factors determining crop productivity and to propose plausible pathways to narrow the gap between actual and potential yield. A synthesis study was conducted on data available from performance trials and by reviewing >100 reports in peer-reviewed journals, extension publications, and websites. The main outcomes obtained from this synthesis suggested that canola attainable yield could be 4 Mg ha⁻¹ with a potential maximum yield of 7 Mg ha⁻¹. However, actual average yields in North America region were ~1.7 Mg ha⁻¹ for the period 2000 to 2014. Available in-season water, water distribution at critical stages, and nutrient supply (soil plus fertilizer) all contribute to a significant portion of canola yield. Other management factors such as seeding rate, rotation, and cultivar selection substantially affect plant performance. Tillage might have an economic and environmental effect, but overall, the outcome of the meta-analysis did not show significant effect on yield. The review suggests that water supply, balanced nutrition, early planting (for both winter and spring types) in shallow depth (10–19 mm), high seeding rate (6 kg ha⁻¹), and diverse rotation (canola every 3 or 4 yr) are among the best management practices to increase yields. Future lines of research should focus on improving planting operations that diminish early-season heterogeneity, fine-tuning optimal seeding rates based on modern varieties at varying yield environments, and searching for compatible hybrids to replant without heterogeneity at harvest.

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**Abbreviations**: BMP, best management practice.
use of regular postemergence herbicides designed to control grassy weeds (Zollinger, 2013). In addition, several spring canola hybrids have Roundup Ready technology that allows control of both broadleaf and grassy weeds susceptible to glyphosate herbicide (O'Donovan et al., 2006). Canola hybrids resistant to herbicides such as glufosinate (Liberty Link), triazine, and imidazolinone are currently available as another set of technology to improve weed control in canola (Beckie, 2013).

Due to its industrial importance, canola production has grown from 5 to ~19 Tg from the early 1990s until 2014 in the North American region (FAO, 2014). A large proportion (90%) of North America canola production occurs in Canada (USDA-ERS, 2012). From a US production area standpoint, canola has grown from 100,000 ha in the early 1990s to ~1 million ha, with presence in the states of Idaho, Kansas, Minnesota, Montana, North Dakota, Oklahoma, Oregon, and Washington. North Dakota alone represents more than half of US canola production (USDA, 2015).

Best management practices (BMPs) for winter and spring canola limit crop exposure to the right amount of necessary environmental conditions (e.g., temperature, radiation) and available resources (e.g., water availability, available nutrients) at each development stage and prevent damage from pests and disease. These canola BMPs include the right combinations of genotype (e.g., open-pollinated vs. hybrids), crop rotation, seeding rate, row spacing, planting depth, and in-season management decisions such as herbicide, plant growth regulators, nutrient applications, and irrigation (Kutcher et al., 2013; Chapagain and Good, 2015; Jones and Olson-Rutz, 2016). The impact of environmental and crop management factors on canola yield, oil quality, and seed composition were discussed in multiple research reports in North America and elsewhere (Nuttall et al., 1992; Pritchard et al., 2000; McCartney et al., 2004). Since most published research was focused on one factor at a time, the mechanism of how multiple factors interact to influence canola yield and the level of their significance was rarely reported.

The objectives of this review were to synthesize and quantify (via meta-analysis) the effect of diverse management factors on canola yields and to propose possible avenues for narrowing the yield gap, defined as potential minus actual yield. Potential canola yield is defined as the highest yield obtained when resources are not limited, and actual yield is defined as yield attainable with the existing production and environmental constraints. To meet the aforementioned objectives, >100 reports in peer-reviewed journals, extension publications, and websites were reviewed, and a large database on canola production was constructed for the purpose of this review.

Additional yield and yield component data were collected across the literature for the North American region. Yield potential is defined as yield of a crop when resources are not limiting and management and environment are optimal (Evans and Fischer, 1999). Given this definition, a plant under low plant density (isolated plant) and in a resource-rich environment can be used to explore yield potential, assuming that yield decreases when plant density increases as a result of competition for limited resources. If resources are not limited, each plant performs to the best-recorded performance of a single canola plant. With this assumption, canola yield potential was calculated using the maximum attainable yield component (pod number, seeds per pod, and seed weight) previously recorded in the scientific literature. Attainable yields and actual yields are defined as yields from performance trials and most frequently reported producer-level yields, respectively (Chapagain and Good, 2015).

According to papers reviewed on factors that affect canola yield and the gaps between potential, attainable, and actual yields, a framework was developed to depict factors responsible for canola yield and their significance (Fig. 2). This theoretical framework (Fig. 2) was developed according to what has been learned from the literature review database collected, but among the key studies related to the framework were (i) yield gap analyses by Mueller et al. (2012) and Chapagain and Good (2015); (ii) the impact of temperature and precipitation on canola yield, presented by Kutcher et al. (2010) and Assefa et al. (2014); (iii) the impact of management and environment interaction on yield, presented by Nuttal et al. (1992) and Cutforth et al. (2006); and (iv) yield and yield components of canola as affected by management and environment, documented by McGregor (1981, 1987).

A scientific screening of research literature on Web of Science and Google was performed to select research papers that reported canola crop water, nutrient, planting date, planting depth, seeding rate, tillage, residue management, and rotation effects one at a time. Papers were retrieved using the keywords “canola or rapeseed” in their title and each one of the following: “crop water,” “nutrient,” “planting date,” “planting depth,” “seeding rate,” “tillage,” “residue management,” “rotation,” “plant density,” “seeding depth or planting depth,” “yield components or pod number or seed weight or seed number,” “yield” as a topic (one of this at a time), and “US or Canada or North America” as an address. In addition, unpublished data available to us were included. The main criteria for inclusion of a publication were mainly availability of canola yield information and North American geographical location. When a

MATERIALS AND METHODS

Yield data from hybrid performance trials for the period 2011 to 2015 conducted across Canada and the United States were collected from progress reports available to the public (Canola Council of Canada, 2011–2015; Kansas State University, 2011, 2012, 2013,2014, 2015; Montana State University, 2012, 2013, 2014, 2015; Grafstrom et al., 2013, 2015; North Dakota State University, 2013, 2014, 2015, 2016). The distribution of yield and plant height, and descriptive statistics such as mean, median, standard deviation, maximum, minimum, and variation of the performance trials were analyzed in R (R Development Core Team, 2012; Fig. 1).

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Four approaches were followed to present the results as related to the amount of data available and possibility of analysis. The first approach to this review was to aggregate research recommendations of the impact of a factor on yield across literature. This approach was the only approach used for factors with a limited amount of research that made it difficult to bring data together for reanalysis or meta-analysis. For example, when we studied planting depth and yield relation, there were few studies, and these studies did not have an overlapping or common planting depth to aggregate them for reanalysis. For such factors (planting depth and row spacing), a summary was prepared according to recommendations of the articles. Based on the aggregated findings, a path was suggested of BMPs for these factors as related to their effects on canola yield.

In a second approach for other factors, in addition to summarizing the different recommendations across research reports, data from the same literature were collected and reanalyzed as a synthesis analysis type of review. Crop water requirement, crop water use, and yield data were collected, aggregated, and analyzed (regression analysis). For seeding rate, plant density, and yield reported across papers, data were divided into yield environments. Specific yield environmental relationships were analyzed between yield and seeding rates.

The third approach was a meta-analysis type of review. In addition to the presentation of findings of papers, collected data on the impact of alternative factors (tillage vs. no-till, rotation vs. monocrop) was analyzed via utilization of the meta-analysis technique (when sufficient papers and observations were available). For the meta-analysis, a forest plot (Lewis and Clarke, 2001) was used to summarize the effect of each component evaluated.

The fourth approach in our review was analysis of the deviation of yield from the mean of the study. Deviation of yield was calculated by subtracting the mean yield of the study from the yield of each location or plant height category. This approach was applied (i) when we summarize how yield deviated from the mean in favorable and unfavorable environments (year and location), and (ii) to demonstrate how plant agronomic performance (plant height) can be a good indicator of yield. Similarly, relative percentage of yield was used to study the impact of planting date on yield. The relative percentage meta-analysis was conducted, for some of management factors, availability of yield data “with” and “without” the management factor was among selection criterion.

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yield was calculated by dividing yield at each planting date by maximum yield, expressed as a percentage.

RESULT AND DISCUSSION

Yield

The mean and median canola yield from variety trials for the 2011 to 2015 period was 3.4 Mg ha\(^{-1}\) (Fig. 1a) for spring varieties and 2.5 Mg ha\(^{-1}\) for winter canola varieties (Fig. 1c). Since variety trials are managed for yield-limiting factors, the yield from these trials fits into the definition of attainable yield for the region (Chapagain and Good, 2015). With the assumption that the best performance of a single plant grown at a low density depicts no resource limitations, we approximated 7 Mg ha\(^{-1}\) at a density of 18 to 20 plants m\(^{-2}\), 600 pods plant\(^{-1}\), 20 seeds pod\(^{-1}\), and 3 g 1000 seed\(^{-1}\) (McGregor, 1987). Maximum yields (5 to 7 Mg ha\(^{-1}\)) previously reported by Assefa et al. (2014) and Harker et al. (2012b) were close to the potential yield found and projected in this study (Fig. 1a and 1c). However, actual average yield of canola for the North American region in the 2000 to 2014 period was 1.7 Mg ha\(^{-1}\) (1.72 Mg ha\(^{-1}\) for Canada and 1.65 Mg ha\(^{-1}\) for the United States; FAO, 2014), which is 50 and 75% lower than attainable and potential yields, respectively. The most frequently reported North American canola yields found in this review (according to the distribution in Fig. 1) were in the range of 0 to 4 Mg ha\(^{-1}\) due to various yield-limiting factors affecting the crop.

Factors that determine and indicate canola production were divided into four groups according to level of importance: (i) resource and weather, (ii) management and genetic, (iii) agronomic performance, and (iv) yield component factors (Fig. 2). Resource and weather are the primary factors significantly affecting canola yield. Those factors dictate management, affect agronomic performance, and determine canola yield components and, consequently, final yield (Nuttal et al., 1992; Kutcher et al., 2010; Riar et al., 2016). A limitation in resource and weather factors is a major cause of the significant yield differences between “dry and hot” versus “cool and wet” environments, of site yield differences (due to soil and weather), and eventually of major differences in potential and actual yield when management is optimal (Fig. 2). Average yield advantage for the years and sites with the highest impact would be ~60% higher than the lowest yield.
scenarios (Fig. 3). Water and nutrients are resources that, when limited, can be fully or partly alleviated by irrigation and fertilizer applications. Length of the growing season, effect of temperature (heat and cold stress), and solar radiation would be among resource and weather factors that cannot easily be compensated by crop management. In a global yield gap analysis, Mueller et al. (2012) determined that 60 to 80% of the global yield gap for major crops is due to resource and weather (climate, irrigation, and fertilization) factors.

In addition to weather and resource factors, crop management factors determine crop performance and final yield. Management and genetics include planting date, planting depth, seeding rate, row spacing, rotation, and hybrid or variety selection (Cutforth et al., 2006; Chapagain and Good, 2015). Even if weather and resource factors are not limited, yield will be below the attainable level if canola is not planted at the right time, rate, and depth, or if proper rotation, cultivar selection, and required residue cover are not achieved. Therefore, in the sections below, a more in-depth analysis of selected resource and management factors is pursued with the goal of aggregating and, if possible, quantifying those effects in canola yields.

**Resource-Related Factors**

**Crop Water Requirement**

Water requirement is mainly driven by crop demand but is regulated by the environment; this water requirement varies by specific site-years and is not easily expressed as a constant value (Assefa and Staggenborg, 2010; Aiken et al., 2011). According to research in the northern Great Plains region, a minimum seasonal water requirement in the range of 121 to 160 mm season$^{-1}$ was reported for canola to survive without production (Johnston et al., 2002). Additional water above this minimum water requirement increases canola yield at a rate ranging from 6.9 to 7.7 kg ha$^{-1}$ mm$^{-1}$. A similar minimum seasonal water requirement (ranging from 121 to 123 mm season$^{-1}$) and yield increases at a rate of 7.7 kg ha$^{-1}$ mm$^{-1}$ (to a maximum of 582 mm season$^{-1}$) were also documented by other researchers (Nielson, 1997; Hergert et al., 2016).

Seasonal water distribution throughout the season is more critical for successful canola production than total water supply (Hergert et al., 2016). Daily water requirement during the early stages of canola (emergence to rosette) is 1 mm d$^{-1}$, steadily increasing from 2 to 5 mm d$^{-1}$ at late rosette to the bud stage, and up to 6 mm d$^{-1}$ at critical stages such as flowering and pod set (Diepenbrock, 2000). Water and other resource limitation at these critical stages (flowering and pod set) define attainable yield. Water requirement declines sharply after seed set to harvest (Hergert et al., 2016). From a study in Nebraska, Pavlista et al. (2016) concluded that >200 mm of water is required...
for adequate vegetative growth, and that >400 mm of water is necessary for high yield (3 Mg ha⁻¹).

In summary, when all data from previous references were aggregated, an average of 7.2 kg ha⁻¹ yield gain for each millimeter of water above 125 mm (for up to 600 mm) was found for canola (Fig. 4). To produce canola to its potential, proper quantities and timing of available water supply (precipitation plus irrigation) are needed. Water limitation and/or excessive water can cause nutrient limitation, poor growth, and disease outbreaks (Franklin et al., 2005; Bedard-Haughn, 2009). Research on winter canola yield response to irrigation water and interaction with variety and hybrids for the North American region is limited and remains a research gap.

**Nutrient Requirements and Fertilizer Response**

Canola productivity depends on available nutrients. At maturity, spring canola N requirement was ~62 kg plant N Mg⁻¹. From this N content, 58% is allocated to seed (N harvest index), with 42% to the stover (Table 1). Nutrient removal for N was 38 kg seed N Mg⁻¹. Plant P requirement was of 12 kg plant P Mg⁻¹, with a P harvest index of 65%. Nutrient removal for P was 8 kg seed P Mg⁻¹ (Table 1). Unlike N and P, a largest proportion of plant K content remained in the stover (84%), with an overall plant K requirement of 45 kg plant K Mg⁻¹. Nutrient removal for K was 8 kg seed K Mg⁻¹ (Table 1). Lastly, overall plant S requirement was 28 kg plant S Mg⁻¹, with a S harvest index of 25%. Nutrient removal for S was 8 kg seed S Mg⁻¹ (Table 1). Similar nutrient requirements were recently reported for winter canola by Ciampitti et al. (2014).

The probability of canola response to N fertilization increases as the soil N-NO₃ test decreases below 100 kg N ha⁻¹ (Soper, 1971). A quadratic model was previously reported for canola yield response to applied N (Soper, 1971; Brandt et al., 2007; Cutforth et al., 2009; Table 2), with yield plateauing when available N reached 100 to 200 kg N ha⁻¹, depending on the environment. A strong interaction between canola response to N fertilizer with soil moisture and S fertilizer was reported (Malhi et al., 2007a; Malhi and Gill, 2007). A split N application with no direct seed-to-fertilizer contact at planting and remaining N sidedressed at approximately the six-leaf stage was suggested as the BMP for N (Grant and Bailey, 1993; Cutforth et al., 2009; Ma et al., 2015).

Canola responds to S fertilizer applications under soil conditions where cereals may not. Depending on the site-year, a 3 to 30% yield increase was reported for plots with S application over the control (Ma et al., 2015). Application of 10 to 30 kg S ha⁻¹ is generally recommended, but soil testing for S is suggested to determine the need for S application (Malhi et al., 2005; Malhi and Gill, 2006). Sulfate-sulfur, rather than elemental S fertilizers, applied at planting time in broadcast, rather than banding, applications was found to increase S availability and canola yields.

Canola production may require an addition of 20 to 30 kg P ha⁻¹, depending on soil P levels, but in most soils, K fertilizer applications were not recommended (Anderson and Kusch, 1968; Sheppard and Bates, 1980; Nuttall and Button, 1990). Soils with NaHCO₃-extractable P ( Olsen P) below 10 mg kg⁻¹ in 0- to 15-cm depths required addition of P fertilizer (Soper, 1971). On average, a 10% yield increase was reported for P fertilizer applied over the control (McKenzie et al., 2003). Due to an abundance of K in the soil and relatively low K requirements for canola, yield response to fertilizer K applications was scarce.

In summary, a canola plant takes up to 62–12–45–28 kg of plant N–P–K–S Mg⁻¹ yield. Similar total canola nutrient requirements (60–15–65–12 kg of plant N–P–K–S Mg⁻¹ yield) were previously documented in a revision for cereals, oilseed, and industrial crops (Ciampitti and Garcia, 2008). However, exact nutrient applications vary by soil test (soil nutrient supply), target yield, crop rotation, and intensification of cropping systems (with or without cover crops). A split application and no contact between seed and fertilizer are recommended for N fertilizers. A soil test that can accurately determine the need for S fertilizer still remains a research gap; however, in absolute values, plant S requirement is relatively small and fertilizer S needs to always be warranted for high-yielding canola production systems.

**Management and Genetic Factors**

**Planting Date**

The effect of planting date on both winter and spring canola yield was studied, and its significance was reported in multiple research papers. A 1.7% yield decline per day
Table 1. Synthesis for yield and nutrient content (seed/stover) for nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) of canola at different yield levels and environments (location).

<table>
<thead>
<tr>
<th>Author</th>
<th>Yield</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>S</th>
<th>Site location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuttall and Ukrainetz, 1991</td>
<td>0.98–1.24 kg ha⁻¹</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4/15</td>
<td>Northern Saskatchewan</td>
</tr>
<tr>
<td>Jackson, 2000</td>
<td>2.0 Mg ha⁻¹</td>
<td>62/48</td>
<td>13/8</td>
<td>17/123</td>
<td>7/44</td>
<td>Montana, USA</td>
</tr>
<tr>
<td>Malhi et al., 2007b</td>
<td>2.2 Mg ha⁻¹</td>
<td>76/41</td>
<td>13/4</td>
<td>22/123</td>
<td>10/27</td>
<td>Saskatchewan, Canada</td>
</tr>
<tr>
<td></td>
<td>2.0 Mg ha⁻¹</td>
<td>68/30</td>
<td>13/4</td>
<td>16/54</td>
<td>9/15</td>
<td>Saskatchewan, Canada</td>
</tr>
<tr>
<td></td>
<td>1.5 Mg ha⁻¹</td>
<td>61/42</td>
<td>10/4</td>
<td>15/60</td>
<td>8/13</td>
<td>Saskatchewan, Canada</td>
</tr>
<tr>
<td></td>
<td>1.1 Mg ha⁻¹</td>
<td>44/57</td>
<td>8/6</td>
<td>11/39</td>
<td>6/15</td>
<td>Saskatchewan, Canada</td>
</tr>
<tr>
<td>Karamanos, 2013</td>
<td>2.0 Mg ha⁻¹</td>
<td>76/49</td>
<td>46/19</td>
<td>24/81</td>
<td>13/11</td>
<td>Western Canada</td>
</tr>
<tr>
<td>Ma and Zheng, 2016</td>
<td>2.0 Mg ha⁻¹</td>
<td>64/39</td>
<td>10/7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>2.8 Mg ha⁻¹</td>
<td>98/54</td>
<td>15/11</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>2.6 Mg ha⁻¹</td>
<td>93/47</td>
<td>16/9</td>
<td>–</td>
<td>–</td>
<td>Ottawa, Canada</td>
</tr>
<tr>
<td></td>
<td>3.1 Mg ha⁻¹</td>
<td>117/70</td>
<td>20/15</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>3.3 Mg ha⁻¹</td>
<td>130/78</td>
<td>28/17</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2. Quadratic fit for relationship between canola yield and N fertilizer calculated from data, figures, or equations given by the authors for different conditions (dryland vs. favorable, with S fertilizer or without, for hybrids vs. open-pollinated, or years).

<table>
<thead>
<tr>
<th>Author</th>
<th>Quadratic fit equations</th>
<th>( R^2 )</th>
<th>Max. yield (Mg ha⁻¹)</th>
<th>N rate at max. yield (kg N ha⁻¹)</th>
<th>Location</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soper 1971</td>
<td>( y = -0.0157x^2 + 9.1778x + 502.23 )</td>
<td>0.96</td>
<td>1.8†</td>
<td>200 Mg ha⁻¹</td>
<td>Canada</td>
<td>From graph</td>
</tr>
<tr>
<td>Brandt et al., 2007</td>
<td>( y = -0.2059x^2 + 39.374x + 65.795 )</td>
<td>0.20</td>
<td>2.6</td>
<td>110 kg N ha⁻¹</td>
<td>Scott, Canada</td>
<td>From data</td>
</tr>
<tr>
<td>Brandt et al., 2007</td>
<td>( y = -0.032x^2 + 8.515x + 1345.6 )</td>
<td>0.33</td>
<td>2.1</td>
<td>137 Mg ha⁻¹</td>
<td>Melfort, Canada</td>
<td>From data</td>
</tr>
<tr>
<td>Brandt et al., 2007</td>
<td>( y = -0.0561x^2 + 11.504x + 1106.7 )</td>
<td>0.17</td>
<td>2.1</td>
<td>139 Mg ha⁻¹</td>
<td>India Head, Canada</td>
<td>From data</td>
</tr>
<tr>
<td>Gan et al., 2007</td>
<td>( y = -0.020x^2 + 8.0x + 1300 )</td>
<td>–</td>
<td>1.7</td>
<td>100 kg N ha⁻¹</td>
<td>Canada</td>
<td>Graph, data</td>
</tr>
<tr>
<td>Mahli et al., 2007a</td>
<td>( y = -0.034x^2 + 11.966x + 1656 )</td>
<td>0.96</td>
<td>2.7</td>
<td>150 kg N ha⁻¹</td>
<td>Canada</td>
<td>Favorable</td>
</tr>
<tr>
<td>Mahli et al., 2007a</td>
<td>( y = -0.05x^2 + 11.837x + 1011 )</td>
<td>0.97</td>
<td>2.7</td>
<td>150 kg N ha⁻¹</td>
<td>Canada</td>
<td>Dry conditions</td>
</tr>
<tr>
<td>Mahli and Gill, 2007</td>
<td>( y = -0.0401x^2 + 4.7113x + 620.56 )</td>
<td>0.05</td>
<td>1.7</td>
<td>100 kg N ha⁻¹</td>
<td>Canada</td>
<td>0 kg S ha⁻¹</td>
</tr>
<tr>
<td>Mahli and Gill, 2007</td>
<td>( y = -0.0324x^2 + 9.1038x + 646.44 )</td>
<td>0.16</td>
<td>2.5</td>
<td>150 kg N ha⁻¹</td>
<td>Canada</td>
<td>30 kg S ha⁻¹</td>
</tr>
<tr>
<td>Cutforth et al., 2009</td>
<td>( y = -0.0228x^2 + 9.907x + 1232 )</td>
<td>0.81</td>
<td>2.4</td>
<td>200 kg N ha⁻¹</td>
<td>Canada</td>
<td>Hybrid</td>
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<tr>
<td>Cutforth et al., 2009</td>
<td>( y = -0.0354x^2 + 10.025x + 1013 )</td>
<td>0.86</td>
<td>1.8</td>
<td>150 kg N ha⁻¹</td>
<td>Canada</td>
<td>Open pollination</td>
</tr>
<tr>
<td>Ma and Herath, 2016</td>
<td>( y = 0.0059x^2 + 5.4045x + 1597 )</td>
<td>0.84</td>
<td>2.7</td>
<td>150 kg N ha⁻¹</td>
<td>Ontario, Canada</td>
<td>Year: 2011</td>
</tr>
<tr>
<td>Ma and Herath, 2016</td>
<td>( y = -0.0562x^2 + 15.533x + 2396.3 )</td>
<td>0.90</td>
<td>3.5</td>
<td>150 kg N ha⁻¹</td>
<td>Ontario, Canada</td>
<td>Year: 2013</td>
</tr>
</tbody>
</table>

† Maximum yields and N rate are based on reported data not based on the maximum in quadratic fit.

plus reduced oil quality for delayed spring canola planting from late April to late May was documented by McKenzie et al. (2011) and Angadi et al. (2004). A yield advantage from late March to late April planting compared with earlier in February or late in May or June was also reported for spring canola in the Northern US Great Plains region (Kirkland and Johnson, 2000; Chen et al., 2005; Pavlista et al., 2011).

A winter canola study comparing different planting dates between mid-September and late-October (Begna and Angadi, 2016) suggested a reduction in canola biomass and yield with late planting dates. Similarly, Holman et al. (2011) suggested late August to the first week of September as the optimal planting timeframe for winter canola in the Southern Great Plains region (southwestern Kansas). Additionally, a similar yield advantage for early-planted winter canola was presented by Assefa et al. (2014) from an analysis of variety trials (across the United States) and experimental data (Manhattan, KS), with four planting dates between late August and early October.

Early spring- or fall-planted canola provides an advantage since the heat-sensitive reproductive stages of development (gamete development, flowering, and early stages of rapid seed filling) tend to occur when air temperatures are low. However, soil moisture and soil temperature at planting would be critical factors to consider for proper early canola establishment. For fall planting, earlier planting will include warmer soil temperatures. For spring planting, depending on the year, earlier planting will include cooler soil temperatures (Pavlista et al., 2011).

In summary, early planting of winter canola between late mid-September to early October (240–260 d from January) and planting of spring canola between late March and late April (90–130 d from January) are suggested as...
optimal from the data aggregated in this review analysis (Fig. 5). Finding compatible spring varieties to replant when survival of winter canola is low, keeping uniform growth (even more important for the winter canola types), and better understanding of seed quality formation would be helpful research to explore in relation to planting date.

**Planting Depth and Planter Configuration**

Research studies comparing different planting depth (6–50 mm) did not find a consistent yield difference at the end of the season but found significant differences in agronomic characteristics such as emergence and disease occurrence. Hanson et al. (2008) reported that percentage of emergence and planting density were greater for the 19-mm than the 38-mm planting depth. Prior to that, Lamb and Johnson (2004) found 24 to 41% lower pure live seed emergence for 50 versus 25-mm planting depth. However, Lamb and Johnson (2004) also reported that disease incidence was higher in the 25-mm planting depth than at 50 mm. Better plant establishment at an even shallower planting depth (6–12 mm) compared with 25– to 50-mm depth was also reported (Thomas et al., 1994). Shallow planting at a depth of 10 mm compared with 40 mm not only increased percentage of emergence but also shortened days to emergence, days to flowering, and days to maturity and increased early-season canola ground cover (Harker et al., 2012a). However, the effects of shallow planting on flowering time and maturity might be a consequence of the cumulative differences in the time of emergence. Considering emergence as a starting point of phenology, different planting depths should not have an effect on crop development.

Limited information is available about other planting configurations, but similar to planting depth, planter configuration such as planter speed and packing wheel pressure did not significantly affect yield but had effects on certain agronomic characters of canola. Increasing seeding speed from 6.4 to 11.2 k h\(^{-1}\) decreased percentage of emergence (Harker et al., 2012a). The effect of increasing speed on percentage of emergence worsened with deeper planting depth. The effect of packing wheel pressure varied with soil texture. Increasing packing wheel pressure increased percentage emergence in sandy soil, but the reverse was true in a loam sandy soil (Thomas et al., 1994).

In summary, shallow (10–19 mm) is favored over deep (25–50 mm) planting depth. A slow seeding speed and a packing wheel pressure based on soil type should be considered. Further research on how planting configurations (clumping over row), planting depth for modern canola hybrids with improved vigor, and factors affecting successful canola establishment and potential attainable yields should be pursued to evaluate optimal resource utilization and impacts on canola yields.

**Plant Density, Seeding Rate, and Row Spacing**

Scientific literature outcomes on the canola yield-to-plant density relationship presented mixed signals. Positive (Clarke and Simpson, 1978; Harker et al., 2003; Brandt et al., 2007; Hanson et al., 2008), no-effect (Degenhardt and Kondra, 1981; Christensen and Drabble, 1984; Angadi et al., 2003), negative (Kondra, 1975), and site-specific (Kondra, 1977; Gan et al., 2016) canola yield-to-plant density relationships were reported by various researchers. Data gathered from the abovementioned reports and analyzed according to yield environments suggest that the canola yield-to-plant density relationship could depend on the productivity of the environment (Fig. 6). In medium- (1.5–2.5 Mg ha\(^{-1}\)) and high-yielding (>2.5 Mg ha\(^{-1}\)) environments, plant density had a smaller effect on yield (i.e., the yield-to-plant density relationship was generally flat). In low-yielding environments, the yield-to-plant density relationship fitted a quadratic model. The latter

![Fig. 5. Winter and spring canola percentage yield as affected by planting date in days after 1 January. Percentage yield is determined relative to the highest yield of each study. The shaded region indicates a possible window of planting without losing a significant percentage of yield. Studies evaluated include Begna and Angadi (2016), Holman et al. (2011), and Assefa et al. (2014).](8.png)
is in agreement with the yield-to-plant density outcomes reported by Gan et al. (2016). Additionally, Angadi et al. (2003) reported a similar yield level for a wide range of plant densities for a year with above-normal precipitation, whereas yields declined to a lower plant density in drier years, emphasizing the importance of achieving an optimal stand in low-yielding environments.

Canola greatly compensates for low plant density in high-yielding environments (>2.5 Mg ha\(^{-1}\)). Increasing the number of pods (from 20 to 600 plant\(^{-1}\)) on productive branches (racemes) is one of the main compensation mechanisms (McGregor, 1987; Morrison, 1990). Other compensation mechanisms include increasing the number of seeds per pod and individual seed weight. However, from this synthesis analysis, it can be deduced that in a low-yielding environment (with low availability of resources, primarily related to nutrients and water), the plants do not initiate compensation mechanisms; thus, seeding at an optimum rate is the only way to increase yield.

In summary, seeding rates, germination, and emergence percentage determine the final attainable plant density. Due to winter survival rate (in winter canola types), higher seeding density is recommended (Moore and Guy, 1997). Overall, for high-yielding environments, there is a stronger (based on coefficient of determination, \(R^2\)) relationship between seeding rate and plant density than for medium- and low-yielding environments (Fig. 6). Due to compensation and greater emergence and germination in high-yielding environments, seeding rates can go as low as 1.5 to 3.0 kg ha\(^{-1}\) (Morrison, 1990). One research need is to evaluate yield-to-plant density relationship with yield levels >5 Mg ha\(^{-1}\) (information not available on this summary). Higher seeding rates (>6 kg ha\(^{-1}\) spring) are recommended in low- and medium-yielding environments to achieve comparable plant densities. Scarcely research is available on row spacing; narrow (12–15 cm) over wide (30 cm) row spacing was recommended by several researchers for high-yielding canola (Kondra, 1975; Christensen and Drabble, 1984; Angadi et al. 2003, Harker et al. 2003, Brandt et al. 2007, and Hanson et al. 2008) and are classified into three yield environments. Yield values close to planting density zero in panel (a) are not actually at zero planting density but are around 5 to 10 plants m\(^{-2}\). LY, low yield; MY, medium yield; HY, high yield.

**Tillage**

For North America, the impact of tillage on canola production was reported by few researchers. Overall, canola yields were not greatly affected by tillage systems (Azooz and Arshad, 1998; Clayton et al., 2002; Holman et al., 2011). In most of the tested years, Arshad and Gill (1995) did not find a significant yield difference between conventional, no-till, and reduced-till systems but recommended reduced till because it was considered agronomically and environmentally desirable due to somewhat better crop yield than either conventional or no-till systems and two fewer cultivations, which minimizes soil degradation. For no-till systems, yield improvement and benefits to soil water conservation were later documented by several authors (Arshad et al., 1997; Dosdall et al., 1998; Kutcher and Malhi, 2010). On the other hand, specifically for winter canola, others authors reported better yields and improved survival rates for conventional than no-till systems (Borstlap and Enz, 1994; Holman et al., 2011; Assefa et al., 2014), which is also connected to residue management.

A meta-analysis of the effect of no-till over tillage according to data gathered from reported tillage impact studies suggested no significant difference in canola yield between no-till and tillage (Fig. 7). Out of the 11 study locations, five showed a weak tendency for an advantage of conventional over no-till; the other five showed a weak advantage of no-till over tillage, and the one remaining study showed no advantage of tillage treatments. Most of these tillage studies were conducted for a short term.
(<5 yr), except two that were short-term studies in a long-term no-till field (Borstlap and Enz, 1994; Kutcher and Malhi, 2010). There was no consistent correlation observed based on the length of tillage operation because the two long-term no-till field studies concluded differently. Overall, the 95% confidence interval for no-till over tillage effect size was −0.17 to 0.15. However, producers should consider time of planting, disease prevalence, water, economics, and environmental impacts to determine type of tillage practice.

**Rotation and Residue Management**

A significant positive contribution to crop rotation over monocropping is evident from reviewed research. Rotation of canola with other crops and rotation of canola itself with different resistant cultivars reduce soil-borne pathogens and blackleg disease \[Leptosphaeria maculans\] (Desmaz.) Ces. and De Not] incidence (Hwang et al., 2009; Marcroft et al., 2012; Kutcher et al., 2013). A 22% yield increase for canola grown once in 3 yr over continuous canola or an annual yield increase of 0.2 to 0.36 Mg ha\(^{-1}\) for each annual increase in number of crops between canola was reported (Harker et al., 2015a, 2015b). Canola in rotation produced a positive impact on yields of other crops in the rotation. The yield and economic benefit of winter canola in rotation with sorghum \([Sorghum bicolor L. Moench]\), corn \([Zea mays L.]\), cotton \([Gossypium hirsutum L.]\), or soybean \([Gossypium hirsutum L.]\); and a reduction in take-all stem, root rot diseases and Hessian fly \([Mayetiola destructor Say]\) infestation persistent over a wheat–soybean system (Cunfer et al., 2006; Buntin et al., 2007) were evident from the compiled scientific literature investigated on this topic.

A meta-analysis of the impact of continuous wheat or canola production compared with canola–wheat rotation on the yields of the two crops was completed (Fig. 8). A fixed–effect analysis of the effect size of rotation over continuous cropping suggests an overall positive effect size of 0.36 with 95% confidence (0.06; 0.68) for rotation. The scientific literature also recommends a once in 3 or 4 yr rotation of canola as a best rotation practice over more frequent appearances of canola in rotation (Kutcher et al., 2013). A rotation of canola with legumes \([Pisum sativum L. subsp. arvense L.], lentil \([Lens culinaris Medik.],\), and faba bean \([Vicia faba L.]\) over nonlegumes \([Hordeum vulgare L.]\) or wheat) was also found to benefit canola yield (O’Donovan et al., 2014).

The residue management effect on canola was discussed lightly in peer-reviewed journals from various aspects such as (i) type of residue that can reduce disease incidences, (ii) residue accumulation from the planting row, (iii) residue accumulation interaction with tillage, and (iv) from mitigation of frost damage. A significantly better yield of canola grown on other crop residues (barley, oat \([Avena sativa L.]\), or field pea) than on canola residue was reported by Ahmed et al. (2014). No-till management with a 75-mm-wide residue-free strip from the planting row resulted in a 12% yield benefit over no-till management without residue removal from the row (Azooz and Arshad, 1998). Dense, unbroken residue in a no-till system was found to reduce canola emergence and yield (Soon et al., 2005). On the other hand, tall stubble treatments did reduce frost damage and increase survival of winter canola seedlings (Volkmar and Irvine, 2005).

In summary, the positive impact of growing canola in rotation is apparent. However, most rotation studies focus on impacts of canola versus other winter crops. Only limited research data are available on the impact of rotation...
of canola with summer crops such as corn, soybean, and sorghum. For regions such as the US Great Plains, where a summer crop–wheat rotation is dominant, the impact of including canola in rotation remains a research gap. Residue, other than canola itself, removed from planting rows and grown tall to avoid frost damage can reduce disease and increase survival. Like rotation, insightful residue management studies with possible crops adapted to the North American cropping system are lacking.

**Genetics**

Plant breeding transformed an industrial oil crop (rapeseed) into a human and animal consumable crop (canola). A number of herbicide-tolerant canola varieties have been released to effectively manage weeds and increase yield (Harker et al., 2000). For the period from 1970 through 2010, global rapeseed yield has increased at rate of 27 kg ha⁻¹ yr⁻¹ (Rondanini et al., 2012). In their yield and production gap analysis, Chapagain and Good (2015) estimated the contribution of genetics to canola yield to be ~5%. In another study, the use of hybrids and herbicide tolerance was estimated to have increased production by ~7% in Canada (Carew and Smith, 2006). A combination of herbicide-tolerant cultivars with BMPs such as seeding rate and planting date resulted in 41% yield increase compared with low-yielding cultivars, low seeding rate, and late planting (Harker et al., 2003). Breeding gaps include winter canola hybrids tailored to the North American climate, and yield and oil content optimization for North American winter canola to compete on the world market.

**Agronomic Performance**

Agronomic performance is an indicator rather than a factor, since this component reflects the impact of management practices. Agronomic performance of a crop can be used to predict expected yield. For example, canola plants can grow up to a maximum of 182 cm (Fig. 1b and 1d). Notwithstanding, there was no significant difference found in mean plant height of winter and spring canola; the relationship between plant height and canola yield

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**Fig. 8.** A detailed forest plot for the effect of rotation over continuous wheat and canola production from research in the North American region. Studies evaluated include Bushong et al. (2012), Cathcart et al. (2006), Harker et al. (2015b), Schilling et al. (2010) Kutcher et al. (2013), Soon et al. (2005), and Soon and Clayton (2002). MD, mean difference; CI, confidence interval; W, wheat.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Location</th>
<th>Rotation/Continuous</th>
<th>Study</th>
<th>Mean difference</th>
<th>MD 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat (W)</td>
<td>Chickasha, OK, USA</td>
<td>W-C or C-W</td>
<td>Bushong et al., 2012</td>
<td>0.20</td>
<td>0.20 [0.43; 0.83]</td>
</tr>
<tr>
<td></td>
<td>Elmerslie, AB, Canada</td>
<td>W-C or C-W</td>
<td>Cathcart et al., 2006</td>
<td>-0.30</td>
<td>-0.30 [-0.23; -0.36]</td>
</tr>
<tr>
<td></td>
<td>Lacombe, AB, Canada</td>
<td>WW or CC</td>
<td>Harker et al., 2015b</td>
<td>0.25</td>
<td>0.25 [0.09; 0.57]</td>
</tr>
<tr>
<td></td>
<td>Scott, SK, Canada</td>
<td>WW or CC</td>
<td>Schilling et al., 2010</td>
<td>0.40</td>
<td>0.40 [0.23; 0.57]</td>
</tr>
<tr>
<td>Canola (C)</td>
<td>Linda, WA, USA</td>
<td>W-C or C-W</td>
<td>Kutcher et al., 2013</td>
<td>-0.17</td>
<td>-0.17 [-0.30; 0.06]</td>
</tr>
<tr>
<td></td>
<td>Beaverlodge, AB, Canada</td>
<td>WW or CC</td>
<td>Soon et al., 2005</td>
<td>-0.01</td>
<td>-0.01 [-0.03; 0.01]</td>
</tr>
<tr>
<td></td>
<td>Fort Vermilion, AB, Canada</td>
<td>WW or CC</td>
<td>SooanadClayton, 2002</td>
<td>0.00</td>
<td>0.00 [-0.06; 0.06]</td>
</tr>
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</table>

Fixed effect model: 37 (22)
Heterogeneity: squared=0%, tau-squared=0, p=0.9629

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**Fig. 9.** Relationship between plant height and yield of canola (calculated as the deviation from the mean yield value at each site). Note that the best yields are possible on best-performing plants, meaning that yields above average (shaded region) were primarily related to taller plants (>100 cm) for winter and spring canola. Canola plant <100 cm produced in overall less yield than the average. Error bars reflect the standard error for each observation. Data for this graph are the hybrid trials data across Canada, South Dakota, Montana, Minnesota for (a) spring canola type and (b) winter canola trials across the United States, similar to Fig. 1.
showed a significant correlation (Fig. 9). Above-average yields were always from agronomically well-performing crops (i.e., a yield of 4 Mg ha\(^{-1}\) and above was not achieved from plants that grew 75 cm or less).

Similarly, seed establishment and winter survival are indicators of successful canola production (Conley et al., 2004; Holman et al., 2011; Assefa et al., 2014). If canola seedlings are not well established and/or winter survival is significantly low, it is intuitive to expect a yield well below attainable yields, even if resources and climate are not limiting later in the season. Seed establishment, survival, and growth can be used to introduce in-season precision management to change expected low yields. One of these management systems might be replanting and finding a compatible spring canola for low-winter-survival cases.

In summary, a strong correlation among yield, resource availability, climate during critical growth stages translates into yield indicators or agronomic performance factors (i.e., emergence, stand establishment, plant growth, plant height etc.) to yield relation. Crop performance is a one-time measurement, and any resource limitation or change in weather after a measurement of performance alters the expected yield. However, a best performance is the best indicator of yield, given that resource and weather after performance measurement are not limiting.

### Yield Components and Potential for Future Yield Improvements

Four primary yield components are key to understanding future yield improvements: plants per unit area, pods per plant, and individual seed weight. Yield-to-plant density was mentioned above in the seeding rate discussion section. One of the maximum numbers of pods per plant, at an individual plant scale, was recorded by McGregor (1987) with 601 pods at a low plant density (3 plants m\(^{-2}\)). The number of seeds per pod could range between 10 and 26 seeds (McGregor, 1987; Ma et al., 2015). For seed weight, overall, 1000-seed weight aggregated from this synthesis analysis (Clarke and Simpson, 1978; McGregor, 1987; Angadi et al., 2003; Ma et al., 2015) is ~3.2 g 1000 seed\(^{-1}\). However, maximum seed weight recorded from the previous reports was ~4.5 g 1000 seed\(^{-1}\) (McGregor, 1987).

A significant negative relationship between plant density and pods per plant was documented from the scientific compendium gathered for this synthesis analysis (Fig. 10a). Pods per plant decreased sharply as plant density increased from 0 to 50 plants m\(^{-2}\) and then stabilized afterward. The relationships between other yield components (i.e., pods per plants vs. seeds per pod, and seeds per pod vs seed weight) were weak but positive (Fig. 10b and...
10c). Labra et al. (2017) recently documented that high plasticity in seed weight fully compensated for reductions in seed number. This outcome provides new knowledge for rapeseeds, since the primary focus in previous decades was more oriented towards improving performance by increasing seed number (Diepenbrock, 2000; Gomez and Miralles, 2011).

The tradeoff effect between plant density and pods per plant is what maintains the significant response of canola for available in-season resources. If resources are not limiting and each of the canola plants produces at its individual potential under isolated conditions, then potential canola yield could be ~7 Mg ha\(^{-1}\) with 180,000 to 200,000 plants ha\(^{-1}\) (yield components: pods = 600, seeds per pod = 20, and seed weight = 3.0 g 1000 seed\(^{-1}\)) (Fig. 10d. In the scenario that only half of the potential pods per plant is achieved, then a feasible attainable yield should be 3.6 Mg ha\(^{-1}\), which is equivalent to the average yield of the variety performance tests (Fig. 1). However, due to variation of all factors discussed above, canola actual yield in North America is almost one-third of its potential.

CONCLUSIONS

For the North American region, yield gaps of 75 and 50% are evident between actual and potential or attainable canola yields, respectively. Resources and climate are major yield-limiting factors, and various plant management practices are next in importance. This review suggests that water supply, balanced nutrition (emphasizing the high N and S demands), early planting (for both winter and spring types), shallow depth (10–19 mm), high seeding rate (6 kg ha\(^{-1}\)), and diverse rotation (canola every 3 or 4 yr) are among the BMPs to increase yields.

Future research steps should focus on (i) revisiting water and nutrient demand for modern crop hybrids and varieties; (ii) investigating planting configuration and the effect of plant density and spatial configuration associated with plasticity; (iii) exploring the interaction of modern hybrids with plant density and other planting management factors; (iv) dissecting yield components and exploring cause–effect relationships between yield formation factors at varying productivity environments; (v) understanding the effect of crop rotation and residue of summer row crops on canola establishment and yield; and (vi) exploring winter- and spring-compatible hybrids for replanting purposes without heterogeneity in maturity at harvest.

Conflict of Interest

The authors declare that there is no conflict of interest.

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