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Nitrogen Requirements of Ethiopian Mustard for Biofuel Feedstock in South Dakota

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ABSTRACT

Ethiopian mustard (*Brassica carinata* A. Braun) is a non-food oilseed crop that has received attention for its potential as a low-input biofuel feedstock suitable for production in the semi-arid regions of the Northern Great Plains (NGP). Because *B. carinata* is a new crop to the NGP, the best management practices have yet to be developed. The objective of the study was to evaluate the effects of N fertilizer rate on seed yield, seed oil concentration, and oil yield of *B. carinata* and to determine the economic optimum N fertilizer rates. Field studies were conducted at two locations in South Dakota to evaluate the response of two *B. carinata* varieties to five N fertilizer rates (0, 28, 56, 84, and 140 kg N ha⁻¹) during the 2015 and 2016 growing seasons. Increasing N fertilizer rate increased seed yield and oil yield, each reaching a peak at 84 kg ha⁻¹ N and then slowly decreasing following a quadratic model. On the other hand, increasing N rate linearly decreased seed oil concentration. The economic optimum N rate ranged from 60 to 81 kg N ha⁻¹ depending on cost of N fertilizer and the price of carinata seed. These results show that the N requirement for *B. carinata* is lower than that for many crops grown in the NGP, including corn and small grains. These findings confirm that *B. carinata* requires low N fertility and has the potential for incorporation into cropping systems in the semiarid regions of the NGP.

Core Ideas

- *Brassica carinata* is a new crop in the Northern Great Plains.
- Best management practices including N fertilizer recommendations should be developed.
- Seed yield and oil yield were optimized at 84 kg ha⁻¹ of applied N fertilizer.
- Seed oil concentration decreased linearly at a rate of 0.26 g kg⁻¹ for every 1 kg ha⁻¹ increase in N rate.
- Economic optimum N rate varied from 60 to 81 kg N ha⁻¹.

BRASSICA CARINATA A. Braun is a new crop to the Northern Great Plains (NGP) region. There is a lack of information regarding optimal management practices for the crop, including the best N fertilization rates. This is important because the cost of fertilizer is the greatest expense in crop production, followed by seed costs (Zentner et al., 2002). More specifically, N fertilizer is the greatest energy input in the production of oilseed crops (Gan et al., 2007; Zentner et al., 2002). Using the appropriate N rate is very important to achieve high yields while minimizing production costs and reducing environmental impacts (Gan et al., 2007). *Brassica* species are small-seeded crops that tend to react variably to environmental conditions and are known to be extremely sensitive to seed-placed fertilizer salts (CCC, 2016), but there is limited literature on *B. carinata*.

Nitrogen fertilizer applied at high rates (>100 kg N ha⁻¹) increases lodging in *B. napus*, and this may correspond to reductions in yield potential (Wright et al., 1988). High N rates prolong the vegetative growth stage of *B. carinata*, resulting in taller, top-heavy plants and increased susceptibility to lodging (Pan et al., 2012). Additionally, increases in lodging can trap unwanted moisture, which provides a habitable microclimate for sclerotinia (*Sclerotinia sclerotiorum*) infections to develop. Sclerotinia infections can negatively influence seed and oil yields, which is an important consideration because all *Brassica* species are susceptible to sclerotinia stem rot (Hanson et al., 2008). In addition, severe lodging can impede successful harvesting due to uneven plant heights and non-uniform maturation rates in the field (McKenzie et al., 2011).

Depending on the *Brassica* species, increasing N fertilization rates can reduce days to flowering while increasing the flowering period (Gan et al., 2007). In the NGP, reduction in the number of days to flowering can be beneficial for avoiding high temperatures during the flowering and seed-filling periods (June–July), which can decrease yields. However, increasing applied N may prolong the life of leaves; this, along with the indeterminate flowering habits of carinata, can increase the number of days to maturity (Jackson, 2000; Seepaul et al., 2018; Wright et al., 1988). This can be detrimental in areas with short growing seasons

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Abbreviations: CP ratio, cost of N fertilizer to price of carinata seed; EONR, economic optimum N rate; EOY, economic optimum yield; NGP, Northern Great Plains; NUE, nitrogen use efficiency.

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because harvest can be delayed, risking yield losses due to fall frost in late-maturing varieties (CCC, 2016; Grant and Bailey, 1993; Kutcher et al., 2000). In addition, delayed maturity may result in increases in green (immature) seed production, decreasing seed quality and profitability for producers (CCC, 2016).

High N rates decrease oil concentration in *Brassica napus* (Jackson, 2000; Karamzadeh et al., 2010; Taylor et al., 1991) and in *B. carinata* (Pan et al., 2012). Environmental factors such as temperature and moisture also influence oil concentration in *Brassica* species. Periods of high temperatures and low soil moisture during the flowering and seed-filling periods reduce seed oil concentration in canola (Morrison and Stewart, 2002; Pritchard et al., 2000). Conversely, cool and wet conditions prolong seed maturation, which results in greater oil accumulation (Pritchard et al., 2000), whereas high temperatures reduce the seed-filling period (Faraji, 2012; Zanetti et al., 2009). Oil concentration is often the most important factor in *B. carinata* production, with higher oil content of seeds resulting in higher seed quality and increasing profitability for the producers. Despite the negative correlation between seed oil concentration and applied N, total seed oil yield can still increase with increase in N fertilizer rate (to 100–150 kg ha⁻¹ N depending on the environment), at which point total oil yield increase begins to decline (Harker et al., 2012; Jackson, 2000; Karamzadeh et al., 2010; Pan et al., 2012).

Seed yield is a function of the effects and interactions of many environmental (precipitation, temperature) and soil (texture, fertility, and organic matter content) factors. Overall, seed yield in *B. carinata* increases in response to N fertilizer rate (Hossain et al., 2018; Johnson et al., 2013; Pan et al., 2012). In research conducted in Canada, all *Brassica* species, including *B. carinata*, began to reach maximum yield potential at about 100 kg N ha⁻¹, with some variation among species, although these yields were not significantly different from seed yields at about 75 kg N ha⁻¹ (Gan et al., 2007; Johnson et al., 2013; Pan et al., 2012). Seed yield response to increasing N fertilization rate decreases as N rate for many *Brassica* species increases beyond 100 kg N ha⁻¹, which has been attributed to decreasing N use efficiency (NUE) (Gan et al., 2007; Hocking et al., 2002). In *Brassica* species, high temperatures and drought stress conditions during flowering may result in flower abortion or seed development failure (Gan et al., 2007; Morrison and Stewart, 2002). A combination of drought and heat stress can result in pollination failure, the formation of empty pods, and, subsequently, high yield losses (Gan et al., 2004). Such conditions are common in the semiarid regions of the NGP and have raised concerns over the viability of canola production in these environments. Although concerns regarding canola production in these regions are valid, *B. carinata* is reportedly more heat and drought tolerant than *B. napus* (Pan et al., 2011; Taylor et al., 2010), potentially making it a better candidate for production in the semiarid regions of the NGP.

Although most previous research suggests that increasing N rate could increase seed yield of *B. carinata*, indications are that N requirement varies considerably depending on growing conditions (Hossain et al., 2018). The inverse relationship between seed oil concentration and N fertilization rate means that production goals must be factored into N fertilizer application decisions under local growing conditions. Inappropriate fertilization can result in poor seed oil quality and reduce profitability for growers. The high cost of N fertilizer requires that growers properly

manage N fertilization rate and fertilize at an economic rate. Profitability is influenced by both the cost of N fertilizer and the price of *B. carinata* seed. The objectives of this study were (i) to evaluate the effect of N fertilizer rate on agronomic traits, seed yield, oil concentration, and oil yield of *B. carinata* varieties; (ii) to determine if variety × N fertilizer rate interactions occurred; and (iii) to determine the economic optimum N fertilizer rate for *B. carinata*.

MATERIALS AND METHODS

The study was conducted at two locations, near Brookings (44° 18' 40.8863" N, 96° 47' 54.1957" W) and near Pierre (44° 22' 5.9362" N, 100° 21' 3.4794" W), South Dakota, in 2015 and 2016. The Brookings study was conducted on a Brandt silty clay loam (fine-silty, mixed, superactive, frigid Calcic Hapludolls); the Pierre study was conducted on a Dorna silty loam soil (coarse-silty over clayey, superactive, mesic Fluventic Haplustolls). The previous crop at the Brookings location was winter wheat (*Triticum aestivum* L.) in both years. The previous crops at the Pierre location were teff [*Eragrostis tef* (Zucc.) Trotter] in 2015 and corn (*Zea mays* L.) in 2016. Soil analysis details for each location in each year are shown in Table 1. Soils at each location were sampled in the spring of each year at planting time. Four soil cores were sampled diagonally across each field using a teahandled push probe to a depth of 0 to 15 cm. At the Brookings location, the study was managed using conventional tillage; at the Pierre location, the study was under a no-tillage system.

The experimental design was a randomized complete block design with treatments replicated four times. Treatments included five different N fertilizer rates (0, 28, 56, 84, and 140 kg N ha⁻¹) and two *B. carinata* cultivars ('A110' and 'A120') arranged in a factorial design to give a total of 10 treatments within each replication, for a total of 40 plots per location per year. Nitrogen fertilizer in the form of urea (46% N) was broadcast manually on each plot soon after planting using an automatic hand-held spreader to ensure even application. In 2015, plots were planted on 3 April at Brookings and on 16 April at Pierre. In 2016, the planting dates were 26 April at Brookings and 14 April at Pierre. Planting was accomplished using a seven-row Hege 500 (Wintersteiger, Innkreis, Austria) at Brookings; seeding at Pierre was done using a Light Duty Grain Drill (Almaco, Nevada, IA). Individual plot size was 1.6 × 9.1 m (14.6 m²) at Brookings and 1.6 × 8.2 m (13.1 m²) at Pierre. Each plot had seven rows set 22 cm apart. The seeding rate was 11 kg ha⁻¹ at both locations.

Weeds were managed with pre-plant application of Prowl H₂O [Pendimethalin:N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzamine] (BASF, Research Triangle Park, NC) herbicide at both locations and in both years applied at a rate of 0.86 kg ha a.i. and incorporated to a 5-cm depth. Herbicide was applied ~2 wk before planting for both locations and years. Once the crop had emerged, weeds were manually removed from each plot as necessary.

The number of days to maturity was recorded when 50% of pods on the main stem of plants within a plot had turned yellow. Plant height was determined by measuring five random plants within each plot from the soil line to the top of the plant and averaging the height. Yield was determined by harvesting whole plots using a crop research combine (8XP; Kincaid Equipment and

Table 1. Site description and soil characteristics at the 0- to 15-cm depth for the two South Dakota locations where studies were conducted in 2015 and 2016.

Location, year	Previous crop	pH	Soluble salts	Organic matter	NO ₃ -N	Olsen-P	K
			Mmho cm ⁻¹	g kg ⁻¹	kg ha ⁻¹	mg kg ⁻¹	mg kg ⁻¹
Brookings							
2015	Winter wheat	7.1	0.4	48	24	19.0	160
2016	Winter wheat	5.6	0.3	46	46	10	235
Pierre							
2015	Teff	6.8	0.6	34	36	21.7	626
2016	Corn	6.1	0.2	30	21	21.7	426

Manufacturing, Haven, KS) with the assistance of the H2 High Capacity GrainGage (Juniper Systems Inc., Logan, UT). In 2015, *B. carinata* was harvested on 12 August at Brookings and on 14 August at Pierre. In 2016, *B. carinata* was harvested on 9 August at Brookings and on 6 August at Pierre. Seed from each plot was dried to a constant weight, cleaned, and sieved before weighing to determine seed yield. Subsamples of the harvested dry seed were collected and placed into individual manila envelopes for oil content determination. Seeds from two replications for all N fertilizer treatments were sent to SGS Mid-West Seed Services, Inc. (Brookings, SD) for oil content analysis using a hexane solvent extraction. The results of this analysis were used to calibrate a Minispec mq10 NMR Analyzer (Bruker, Billerica, MA) that was then used to analyze seed for oil content for all seed samples from both locations and in both years (results reported as percentage oil on a dry matter basis). Seed oil concentration was calculated by converting percentage oil to oil concentration in g kg⁻¹ of dry weight. Total oil yield (kg ha⁻¹) was determined by multiplying the total seed yield (kg ha⁻¹) by seed oil content (g kg⁻¹).

All data were analyzed using PROC MIXED in SAS Version 9.4 (SAS Institute, Cary, NC). Years and replications were considered as random effects; all other effects were considered fixed. Initially, a test for homogeneity of variance was conducted, and variance was found to be homogeneous for all traits. A combined analysis was therefore conducted for all data collected from the Brookings and Pierre locations over 2 yr (2015 and 2016). Fisher's protected LSD test (<0.05) was used to compare the differences among treatments.

Linear and quadratic models were fit to seed yield, oil yield, and oil concentration data using SigmaPlot Version 14.0 (Systat Software, Inc.) to examine the response to N fertilizer rate. The choice of the best model was based on model significance (significantly different from zero based on *t* test at *P* = 0.05) and *R*² value (Belanger et al., 2000; St. Luce et al., 2015). A Shapiro-Wilk test was used to test for normality. The quadratic model was considered the best choice to describe seed yield and oil yield relationship to N rate; the linear model best described the relationship between N rate and oil concentration in the seed.

Yield data, averaged over years and locations, were used to perform an economic optimum N rate (EONR) analysis. The EONR was defined as the N fertilization rate where \$1 of additional N fertilizer returned \$1 in seed yield. In short, EONR is the N rate that produces the greatest dollar return to N and is a valuable tool to maximize price margins for producers (Camberato and Nelson, 2017; Williams et al., 2007). The quadratic model was used to calculate the EONR and the economic optimum yield by plotting seed yield (kg ha⁻¹) against N rate (kg N ha⁻¹). The relationship between the cost of N fertilizer to the

price of *carinata* seed (CP ratio; St. Luce et al., 2015) is difficult to predict; therefore, we calculated the EONR based on a range of CP ratios beginning in 2015 when the study was initiated to the current CP ratio. Thus, a total of four urea N fertilizer costs were used (1.10 US\$ kg⁻¹ in 2015, 0.88 US\$ kg⁻¹ in 2016, 0.85 US\$ kg⁻¹ in 2017 and 0.84 US\$ kg⁻¹ in 2018; C. Reese, personal communication, 2018). The price of *B. carinata* during this period ranged from 0.30 US\$ kg⁻¹ (USEPA, 2015) to 0.37 US\$ kg⁻¹ (Wright, 2017) to 0.41 US\$ kg⁻¹ (T. Sitter, personal communication, 2017). The CP ratios used in calculating EONR range from 2.05 to 3.67. The EONR was then calculated as:

$$\text{EONR} = \frac{(\text{CP} - b)}{2c}$$

where *b* is the linear coefficient in the quadratic equation, and *c* is the quadratic coefficient in the quadratic equation. The economic optimum yield (EOY) was calculated by substituting the EONR in the quadratic equation and solving the equation (St. Luce et al., 2015).

RESULTS AND DISCUSSION

Temperature and rainfall data were collected at weather stations located within each farm throughout the crop-growing period in both years (Table 2 and 3). The climate data show that the Pierre location was drier (especially during June and July) and hotter than the Brookings location. Overall, the 2015 growing season had rainfall and temperature conditions closer to the 30-yr average at both locations. The trials were planted in early to late April, and the crop reached the flowering stage 52 to 56 d after planting, indicating that flowering and seed filling occurred in June and July. In 2016, both Brookings and Pierre had lower-than-average rainfall in June and July, coinciding with bolting, flowering, and seed-filling periods, a critical time for seed development and quality. During the critical growth period (June and July) at Brookings in 2015, temperatures exceeded 25°C for 43 d but exceeded 30°C for only 6 d. The year 2016 was much warmer, with temperatures exceeding 25°C for 45 d and exceeding 30°C for 12 d. At Pierre, during the critical growth periods (June and July), temperatures exceeded 25°C for 51 d in 2015 and for 57 d in 2016. The number of days with temperature >30°C were 27 in 2015 and 35 in 2016. In particular, the Pierre location experienced higher temperatures and lower precipitation for a longer duration during this critical growth stage, resulting in lower yields.

Plant height was significantly influenced by N rate (*P* ≤ 0.001) and location (*P* ≤ 0.001), and the location × variety interaction was significant (*P* ≤ 0.003) (Table 4). *Brassica carinata* plants were significantly taller in the 28, 56, 84, and

Table 2. Monthly total rainfall throughout the crop-growing period for *Brassica carinata* grown at Brookings and Pierre, SD, in 2015 and 2016 (numbers in parentheses indicate deviations from the 1981–2010 average).

	Rainfall					
	Apr.	May	June	July	Aug.	Total
	mm					
Brookings						
2015	5.1 (–49.0)	137.2 (+62.3)	43.2 (–65.8)	111.8 (+28.7)	71.1 (–6.9)	368.3 (–30.7)
2016	48.3 (–5.8)	60.2 (–14.7)	66 (–43.0)	124.5 (+41.4)	142.2 (+64.2)	441.2 (+42.2)
Pierre						
2015	12.4 (–33.6)	157.0 (+77.0)	96.2 (+6.4)	58.2 (–7.4)	63.2 (+17.2)	387 (+59.6)
2016	99.6 (+53.6)	30.5 (–49.5)	70.9 (–18.9)	28.5 (–37.1)	54.4 (+8.4)	283.9 (–43.5)

140 kg N ha⁻¹ treatments (104, 107, 108, and 109 cm, respectively) compared with the control (98 cm). Optimal height was achieved at the 56 kg N ha⁻¹ rate (107 cm), with these plants being significantly taller than plants in the control treatment (Table 5) but not differing in height from plants receiving higher N rates. Across years, *B. carinata* plants were significantly taller at Pierre when compared with the Brookings location, with average plant heights of 110 and 102 cm, respectively. The location × variety interaction was significant because there was no difference in plant height between the two varieties at the Pierre location (110 for A110 vs. 108 for A120); however, at Brookings, ‘A120’ was significantly taller than ‘A110’ (104 vs. 100 cm), respectively. These results are in agreement with previous research on canola and *B. carinata*, which showed that plant height increased with increasing N rate (Pan et al., 2012; Wright et al., 1988). The influence of N rate on plant height and therefore lodging (Pan et al., 2012) should be taken into consideration in environments with potential lodging problems, such as areas with high wind speeds and high rainfall.

The number of days to maturity was significantly influenced by N rate ($P < 0.019$), with no other factors or their interactions being significant (Table 4). Days to maturity increased in response to N rate, with a rate of 140 kg N ha⁻¹ resulting in the longest time to maturity. Plants in the control treatment took the shortest time to reach maturity, with values of 114 and 111 d, respectively (Table 5). These results confirm findings from previous studies suggesting that increased N fertilization rates can result in delayed crop maturity due to prolonged periods of vegetative growth (Brown et al., 2008; Jackson, 2000; Wright et al., 1988). Delaying maturity can be beneficial to prolong the growing season, and hence to optimize yields, in environments where growing conditions are favorable for long-season varieties. However, in the NGP, prolonged vegetative growth would delay flowering and seed setting, the two most important growth stages determining yield potential, to later in the season (late-June–July)

when high temperature and drought stress often occur. For this reason, delaying maturity may not be beneficial to the producer; instead, earlier planting dates and promoting earlier and shortened duration of flowering to avoid unfavorable conditions have been shown to increase yield in other *Brassica* species (Gan et al., 2016; Kirkland and Johnson, 2000). Furthermore, the differences in days to maturity among N treatments observed in the present study were small, with an increase of 2 to 3 d, which in most years is not going to make much difference.

Seed yield was significantly influenced by N rate ($P < 0.001$), location ($P < 0.001$), and variety ($P = 0.038$); however, interactions were not statistically significant (Table 4). Seed yield increased in response to N rate, with the greatest seed yields occurring at 84 kg N ha⁻¹ (1868 kg ha⁻¹), although this value was not statistically different from the yield obtained at N rates of 56 or 140 kg N ha⁻¹. These results are similar to earlier findings in canola (Gan et al., 2007) and *B. carinata* (Johnson et al., 2013; Pan et al., 2012; Seepaul et al., 2014). The lowest seed yield of 1421 kg ha⁻¹ was obtained in the control treatment (Table 5). The strong relationship between seed yield and N fertilizer rate followed a quadratic model, with an R^2 value of 0.98. This is similar to previous reports for *B. juncea* (May et al., 2010) and for *B. napus*, *B. rapa*, *B. juncea*, and *Sinapis alba* (Gan et al., 2007). This quadratic relationship is due to the decrease of NUE with increasing N rate (Gan et al., 2007; Hocking et al., 2002). Gan et al. (2007) compared five *Brassica* spp. for response to seven N rates and reported that the amount of N fertilizer required to achieve the maximum seed yield was not the same for all species. *Brassica rapa* required the least amount of N for maximum yield (106 kg N ha⁻¹), whereas the requirement for *S. alba* and *B. napus* was intermediate at 135 kg N ha⁻¹, and *B. juncea* had the highest N requirement for maximum yield at 162 kg N ha⁻¹. In the current study, the highest estimated yield of 1876 kg ha⁻¹ for *B. carinata* was obtained at 108 kg N ha⁻¹ (Fig. 1), suggesting that the crop has high NUE. On average, seed yield was

Table 3. Maximum and average temperature throughout the crop growing period for *Brassica carinata* grown at Brookings and Pierre, SD, in 2015 and 2016 (numbers in parentheses indicate deviations from the 1981–2010 average).

Location, year	April		May		June		July		August	
	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.
	°C									
Brookings										
2015	15.8 (+3.0)	8.7 (+2.0)	18.6 (–0.8)	13.0 (–0.3)	25.1 (+0.1)	19.6 (+0.7)	27.3 (–0.5)	21.7 (+0.6)	25.1 (–1.6)	19.5 (–0.5)
2016	13.8 (+1.0)	7.9 (+1.2)	20.8 (+1.4)	14.6 (+1.3)	27.3 (+2.3)	21.3 (+2.4)	27.1 (–0.7)	21.6 (+0.5)	26.3 (–0.4)	20.9 (+0.9)
Pierre										
2015	17.7 (+2.1)	9.8 (+1.5)	19.3 (–1.8)	12.9 (–1.5)	27.1 (+0.4)	20.6 (+0.6)	30.9 (–0.8)	23.4 (–0.5)	30.0 (–0.6)	22.6 (–0.7)
2016	15.8 (+0.2)	8.9 (+0.6)	22 (+0.9)	14.4 (0)	30.1 (+4.4)	22.2 (+2.2)	32.3 (+0.6)	24.4 (+0.5)	30.2 (+0.4)	22.7 (+0.6)

Table 4. P-values from ANOVA for plant height, days to maturity, seed yield, oil concentration, and oil yield of *Brassica carinata*. Data are combined over two locations in South Dakota (Brookings and Pierre), 2 yr (2015 and 2016), and two varieties.

Source of variation	df	Height	Days to maturity	Seed yield	Oil concentration	Oil yield
Location (L)	1	0.004	0.925	<0.001	<0.001	0.013
Variety (V)	1	0.179	0.089	0.038	0.282	0.083
L × V	1	0.003	0.089	0.559	0.472	0.639
Nitrogen (N)	4	<0.001	0.019	<0.001	<0.001	<0.001
L × N	4	0.831	0.888	0.503	0.306	0.295
V × N	4	0.639	0.515	0.339	0.174	0.295
L × V × N	4	0.258	0.802	0.124	0.229	0.278
Random effects						
Year × L × R		8.9	92.4	201,000	380	11,500
Residual		46.2	5.52	84,000	177	8520

significantly greater at the Brookings location compared with Pierre, with values of 1806 and 1603 kg ha⁻¹, respectively (Table 5). The variety 'A120' yielded significantly greater (1753 kg ha⁻¹) than 'A110' (1657 kg ha⁻¹) (Table 5). Lower seed yields are common in lower rainfall regions with higher maximum temperatures (Gan et al., 2004; Hossain et al., 2018). High temperatures (>25°C) during bud and flowering stages can result in the abortion of flowers in *Brassica* spp. and in the failure of seeds to properly develop (Angadi et al., 2000; Canola Watch, 2016; Gan et al., 2004). Drought stress during the reproductive growth stages creates a hormone imbalance that inhibits pod formation and seed development, causing *Brassica* species to drop damaged flowers and focus energy into younger flowers (Canola Watch, 2016). Drought stress during reproductive development reduces levels of hormones (cytokinins and auxins) that prevent flower and pod abortion, resulting in hormonal imbalances within the plant (de Bouille et al., 1989). Although both locations recorded temperatures higher than 25°C during the critical growth stages, temperatures were elevated for a longer period, and moisture conditions were less favorable at Pierre in both years. The period of potential drought stress during the crucial period of the growing season contributed to the lower yields at the Pierre location compared with the Brookings location.

Seed oil concentration was significantly influenced by N rate ($P \leq 0.001$) and location ($P < 0.001$) (Table 4). Seed oil

concentration decreased at a rate of 0.26 g kg⁻¹ for each 1 kg ha⁻¹ increase in N fertilizer rate (Fig. 2). The linear relationship between seed oil concentration and N rate was very strong ($R^2 = 0.99$). These findings agree with earlier findings that show seed oil concentration decreased linearly in response to increasing N rate in *B. juncea* (May et al., 2010) and in *B. carinata* (Pan et al., 2012). The greatest oil concentration (338 g kg⁻¹) was observed in the control treatment, and the lowest oil concentration (299 g kg⁻¹) was observed in the highest N rate of 140 kg N ha⁻¹ (Table 5). Location had a significant impact on oil concentration, with seed from the wetter environment in Brookings showing greater oil concentrations (347 g kg⁻¹) than seed from Pierre (294 g kg⁻¹). The low oil concentration at Pierre is most likely due to overall lower precipitation and higher temperatures throughout the growing season. Low precipitation, coupled with elevated temperatures and drought conditions at seed filling, lowers oil concentration in *Brassica* species (Gan et al., 2004; Pritchard et al., 2000; Wright et al., 1988). Accelerated growth and short growing seasons in semiarid environments negatively affect seed maturity and oil accumulation, resulting in low seed oil concentrations (Getinet et al., 1996).

Total oil yield was significantly influenced by N rate ($P < 0.001$) and location ($P = 0.013$) (Table 4). Total seed oil yield increased in response to increasing N rate following a quadratic model (Fig. 3), similar to previous reports (Harker et al., 2012; Johnson et al., 2013; May et al., 2010). Optimal

Table 5. Nitrogen fertilization rate, location, and variety effects on plant height, days to maturity, seed yield, oil concentration, and oil yield in *Brassica carinata* grown in South Dakota. Means are averaged over 2 yr (2015 and 2016).

N rate	Height	Days to maturity	Seed yield	Oil concentration	Oil yield
kg N ha ⁻¹	cm		kg ha ⁻¹	g kg ⁻¹	kg ha ⁻¹
0	98c†	111b	1421c	338a	470b
28	104b	113ab	1660b	330b	542a
56	107ab	114a	1736ab	323c	558a
84	108ab	114a	1868a	312d	578a
140	109a	114a	1838a	299e	548a
Location					
Brookings	102b	112	1806a	347a	618a
Pierre	110a	113	1603b	294b	460b
Variety					
A110	104	113	1656b	321	526
A120	101	112	1753a	319	552

† Within each column and each treatment, means followed by the same letter are not significantly different ($P \leq 0.05$).

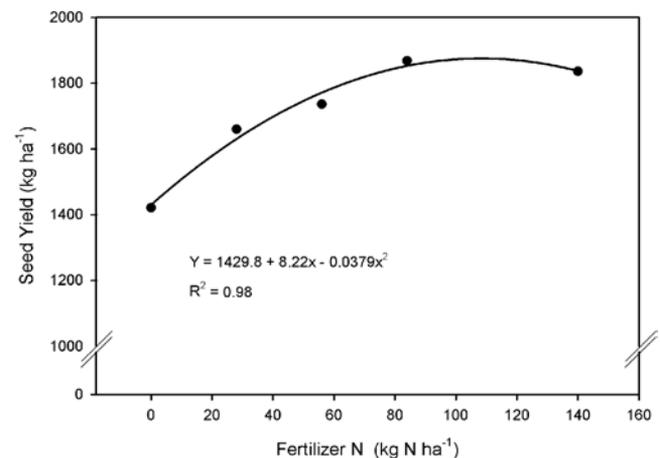


Fig. 1. *Brassica carinata* seed yield as a function of N fertilization rate. Values are averaged over 2 yr, two locations, and two *B. carinata* varieties.

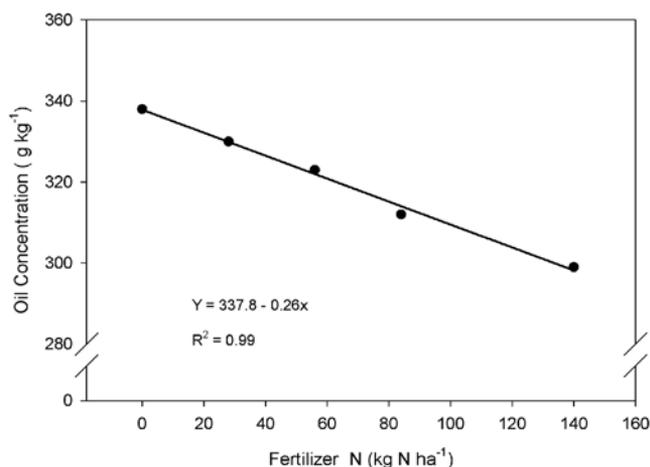


Fig. 2. *Brassica carinata* seed oil concentration as a function of N fertilization rate. Values are averaged over 2 yr, two *B. carinata* varieties, and two locations in South Dakota.

estimated oil yield of 561 kg ha⁻¹ was obtained at 84 kg N ha⁻¹. This is a slightly lower N rate than reported in earlier studies that reported oil yields were optimized at N rates of about 100 to 125 kg N ha⁻¹ (Pan et al., 2012). Total oil yields in this study increased with increasing N rate, with values ranging from 470 to 578 kg ha⁻¹. These values are within the ranges reported in other studies that show oil yields ranging from 185 to 998 kg ha⁻¹ depending on varietal and environmental conditions (Pan et al., 2012). At N rates >84 kg N ha⁻¹, there is a leveling off at which oil yields begin to decrease. Oil yield was significantly influenced by location: as the Brookings location produced greater average oil yields than the Pierre location, with values of 618 and 460 kg ha⁻¹, respectively (Table 5). Higher temperatures during seed filling have a negative effect on seed oil content (Canola Watch, 2016; Faraji, 2012; Pan et al., 2012), explaining the lower oil yields at Pierre where temperatures were extremely high during the seed-filling period.

The EONR and EOY were calculated for 2015 to 2018 based on the cost of N fertilizer for each year and the different carinata seed prices reported over the 4-yr period (Table 6). In 2015, when the cost of fertilizer was high and the price of carinata seed low, the EONR ranged from 60 to 73 kg N ha⁻¹, depending on the carinata seed price. In 2016, the cost of N fertilizer was lower; hence, the EONR was higher, ranging from 70 kg N ha⁻¹ for the lowest seed price of US\$0.30 kg⁻¹ to 80 kg N ha⁻¹ for the highest seed price of US\$0.41 kg⁻¹. When the N fertilizer cost was lower in 2017 and 2018, the EONR was slightly greater, ranging from 71 to 81 kg N ha⁻¹, depending of the selling price of carinata seed (Table 6). The EOY ranged from 1787 kg ha⁻¹ in 2015 when the cost of N fertilizer was extremely high and the carinata seed price was low to 1847 kg ha⁻¹ in 2017 and 2018 when cost of N fertilizer was lower and the price of carinata seed highest (Table 6). The cost of N fertilizer and carinata seed prices fluctuate considerably from year to year. In South Dakota, urea fertilizer cost has decreased over the last 4 yr. *Brassica carinata* is a relatively new crop in the NGP, and most farmers grow the crop under contract. The seed prices used in this paper were obtained from different sources each year (Table 6) and overall show that the value of the crop has increased over the 4-yr period. The EONR ranged from 60 to 81 kg N ha⁻¹, depending on the cost on N fertilizer and

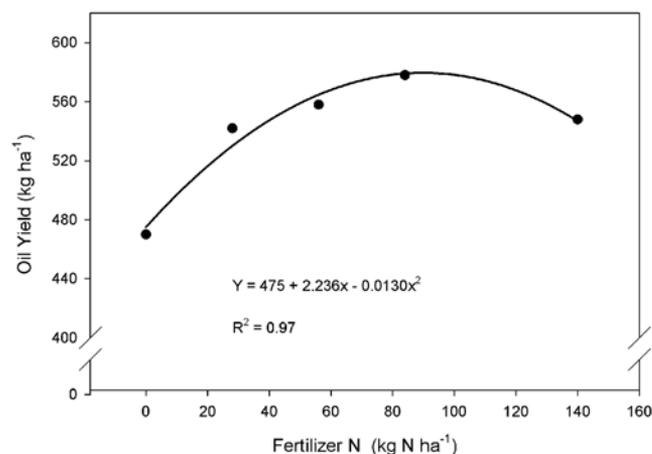


Fig. 3. *Brassica carinata* oil yield as a function of N fertilization rate. Values are averaged over 2 yr, two *B. carinata* varieties, and two locations in South Dakota.

the price of *B. carinata* seed. The response of *B. carinata* to N fertilizer is affected by a number of environmental conditions and management practices; therefore, the economic analysis reported in this paper is specific to the conditions of the study.

CONCLUSIONS

The results of this study suggest that *B. carinata* is very responsive to N fertilizer. A significant quadratic response of seed yield and oil yield to N fertilizer was observed. Seed yield and oil yield were both optimized at 84 kg N ha⁻¹. Seed oil concentration decreased linearly at a rate of 0.26 g kg⁻¹ with every 1 kg ha⁻¹ increase in N rate. The EONR ranged from 60 to 81 kg N ha⁻¹ over a 4-yr period, depending on the cost of N fertilizer and the price of *B. carinata* seed. This suggests that the N requirement for *B. carinata* is lower for optimizing seed yield than that for most crops grown in the NPG region, highlighting the crop's potential as a low-input addition to current production systems. These results suggest that *B. carinata* is a good fit for production in the NGP region of the United States, although high temperatures and drought stress during the reproductive phase can limit yield and seed oil concentration. Planting early in spring to promote early flowering as well as prioritizing development of

Table 6. Nitrogen fertilizer costs (C), carinata seed prices (P), C/P ratios, economic optimum N rates (EONR), and economic optimum yield (EOY) based on C/P ratios for 2015 to 2018.

Year	Cost of N fertilizer	Carinata seed price	C/P ratio	EONR	EOY
	US\$ kg ⁻¹	US\$ kg ⁻¹			
2015	1.10	0.30	3.67	60	1787
		0.37	2.97	69	1817
		0.41	2.68	73	1828
2016	0.88	0.30	2.93	70	1819
		0.37	2.38	77	1838
		0.41	2.15	80	1845
2017	0.85	0.30	2.83	71	1822
		0.37	2.30	78	1840
		0.41	2.07	81	1847
2018	0.84	0.30	2.80	72	1825
		0.37	2.27	79	1843
		0.41	2.05	81	1847

earlier-maturing varieties with a short flowering duration but a more efficient seed set may reduce the yield and the oil concentration penalty associated with high temperature and drought stress during flowering and seed-filling periods.

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