Sowing Date and Tillage Effects on Fall-Seeded Camelina in the Northern Corn Belt

R. W. Gesch* and S. C. Cermak

ABSTRACT

Camelina (*Camelina sativa* L.), a member of the *Brassicaceae* family, can potentially serve as a low-input alternative oil source for advanced biofuels as well as food and other industrial uses. Winter annual camelina genotypes may be economically and environmentally advantageous for the northern Corn Belt, but little is known about their agronomic potential for this region. A 2-yr field study was conducted in western Minnesota to determine optimum fall sowing time for yield and oil content of two winter camelina cultivars in a no-tillage (NT) and chisel-plowed (CP) system. Seeding dates ranged from early September to mid-October. Plants reached 50% flowering as much as 7 d earlier in the NT than the CP system. Plant stands were generally greatest in the NT system, but yields were only greater than those in the CP system during the second year of the study, possibly due to differences in water logging of soil between tillage systems. Seed yield and oil content increased with sowing date up to early October. When sown in October, seed yield and oil content ranged from 419 to 1317 kg ha^{-1} and 282 to 420 g kg^{-1}, respectively. Results indicate that camelina is a viable winter crop for the northern Corn Belt and that seed yields and oil content tended to be greatest when sown in early to mid-October. Moreover, fall-seeded camelina offered good weed suppression without the use of herbicide, supporting the contention that it can be successfully produced with low agricultural inputs.

Camelina, also known as false flax, has a long history of cultivation as an oilseed crop in northern Europe and Scandinavia (Vollmann et al., 1996; Zubr, 1997) and has been shown to have good potential as an alternative oilseed crop for North America (Robinson, 1987; Gugel and Falk, 2006). Camelina oil is highly unsaturated, and its primary fatty acids are oleic (C18:1), linoleic (C18:2), linolenic (C18:3), and eicosenoic (C20:1). Like flax (*Linum usitatissimum* L.), camelina seed oil is high in α-linolenic acid (C18:3), which typically comprises about 30 to 40% of its total oil content (Gugel and Falk, 2006; Vollmann et al., 2007). Camelina oil also is exceptionally high in tocopherol content (Budin et al., 1995), which imparts oxidative stability despite its highly polyunsaturated nature (Ní Eidhin et al., 2003). Because of its physiochemical nature, camelina oil can serve in a variety of food and industrial uses (Zubr, 1997; Vollmann et al., 2007).

Camelina oil has been shown to be suitable for biodiesel production (Fröhlich and Rice, 2005). Recently, it has gained considerable attention as a viable feedstock for aircraft fuel (Scott Johnson, President, Sustainable Oils, personal communication, 2010) and seed has been commercially produced in Montana since 2007 with approximately 8100 ha planted in 2009 and future production is expected to increase (USDA-NASS, 2010). Moreover, camelina seed meal following oil extraction is low in glucosinolate content (Schuster and Friedt, 1998) and may have good value as livestock feed (Korsrud et al., 1978), which will likely add to its economic value.

About 80% of the cost for biodiesel production comes from feedstock cost (Demirbas, 2006). One of the attractions of camelina as a potential biofuel feedstock and rotational crop is that it can be produced with relatively low agricultural inputs (Robinson, 1987; Putnam et al., 1993). Research evidence indicates that camelina has good drought (Angelini et al., 1997; Gugel and Falk, 2006; French et al., 2009) and cold tolerance (Robinson, 1987; Gugel and Falk, 2006), can suppress weeds (Saucke and Ackermann, 2006), and requires relatively low fertility (Robinson, 1987). Additionally, camelina is highly resistant to blackleg disease (*Lepotosphaeria maculans*), which is a significant problem in canola (*Brassica napus* L.) and other mustards (Putnam et al., 1993). Although not as genetically refined as canola, camelina has recently received considerable attention in the way of genetic improvements to seed and oil yield (Vollmann et al., 2007). Seed yields of camelina are comparable to those of mustard species, such as canola and brown mustard (*B. juncea* L.), which have a longer history of breeding improvements (Robinson, 1987; Putnam et al., 1993; Gugel and Falk, 2006). Vollmann et al. (2007) evaluated 30 different camelina genotypes at two field locations in eastern Austria and found seed yields as high as 2800 kg ha^{-1} and oil content as great as 480 g kg^{-1}.

Both winter and spring annual camelina genotypes are known to exist (Putnam et al., 1993). Winter annual crops hardy enough to survive winters in the upper Midwest Corn Belt would have great benefit as cover crops to help prevent soil erosion (Lal et al., 1991) and take up excess N (Staver and Brinsfield, 1998). Winter camelina has been shown to have good winter survival in west central Minnesota, and moreover, may be harvested early enough to allow the production of a second crop (Gesch and Archer, 2009).

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Published in Agron. J. 103:980–987 (2011)
Posted online 18 Apr 2011
doi:10.2134/agronj2010.0485

Camelina was previously agronomically evaluated in Minnesota and shown to be well adapted to its climate and various soil types (Robinson, 1987; Putnam et al., 1993). Robinson (1987) reported no significant yield difference between fall and spring sown camelina in Minnesota. However, in that study, camelina was sown on frozen soil in late fall and presumably did not germinate and emerge until the following spring. Also, it was not specified whether a winter genotype was used.

Because camelina has not been extensively grown in the United States there is little information concerning its agronomic management for this region of the world. Furthermore, there is virtually no information with respect to agronomic evaluation or management of winter genotypes in the northern Corn Belt. Therefore, the objective of the study was to determine the best sowing time to optimize seed yield and oil content for two winter camelina genotypes following a spring wheat crop in a no-tillage or fall chisel-plowed system.

During winter months, snow can insulate the soil leading to warmer soil temperatures, and this insulating factor increases with snow depth (Sharratt et al., 1992). Winter soil temperatures in the northern Corn Belt tend to increase with height of crop residue remaining on the surface due to greater snow capture and accumulation (Sharratt, 2002). A warmer soil environment resulting from snow capture by crop residues can aid in the survival of overwintering plants (Sharratt, 2006). Hence, we hypothesized that the no-till system in our study would lead to greater winter survival and thus, greater yields than the chisel-plow system.

MATERIALS AND METHODS

Cultural Practices

This study was conducted between 2007 and 2009 on a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) at a field site located 24 km northeast of Morris, MN (45°35' N, 95°54' W). The pH of the soil at the study site is typically 7.2 to 7.3, bulk density ranges from 1.03 to 1.20 g cm^{-3} and total organic and inorganic carbon ranges from 34.4 to 27.9 g kg^{-1} in surface to 0.6 m soil depth (Johnson et al., 2010). Two winter camelina cultivars, Joelle and BSX-WG1, obtained from the North Dakota State University Research and Extension Center in Carrington, ND, were sown on four different dates approximately 10 to 14 d apart between early September and mid-October during 2007 and 2008. During both seasons, spring wheat (*Triticum aestivum* L.) was the previous crop.

The experimental design was a split-plot randomized complete block replicated four times. The main plots were split into no-tilled (NT) soil (wheat stubble 10–15 cm) and chisel-plowed (CP) before sowing camelina and the subplots were cultivar by sowing date. Individual plot size was 7.6 by 2 m the first year and 7.6 by 3.7 m the second. Chisel plowing was done to a depth of 20 cm approximately 1 to 2 wk before sowing. Seed of both cultivars was sown at a rate of 6.0 kg ha^{-1} in rows spaced 30-cm apart using a plot drill (Wintersteiger, model PDS 12R). Before sowing camelina, the NT plots were treated with 1.1 kg a.i. ha^{-1} of *N*-(phosphonomethyl)glycine to control volunteer wheat. No other herbicide was applied to plots for controlling weeds.

Soil was tested for N and P in the 0- to 30-cm depth before planting in each season. Ammonium and nitrate N were extracted from dry soil with 1.0 M KCl using the procedure of Mulvaney (1996) and P was extracted with 0.5 M $NaHCO_3$ using the procedure of Olsen and Sommers (1982). Total inorganic soil N (NH_4–N and NO_3–N) was 19 mg kg^{-1} and P was 24 mg kg^{-1} before sowing in 2007, while N and P were 20 and 24 mg kg^{-1}, respectively, before sowing in 2008. Based on the evidence of others (Putnam et al., 1993) and in an effort to minimize inputs, no fertilizer was applied to the camelina the first season, as residual levels of N and P were thought to be adequate. However, after the first season it was believed that N and P levels might be limiting yield potential and thus, during the second year of the study a broadcast application of 78 and 34 kg ha^{-1} of N and P, respectively, was made in late April. Phosphorus was added as diammonium phosphate and N was added as urea (64.7 kg ha^{-1}) and diammonium phosphate (13.3 kg ha^{-1}). Regardless of the difference in fertility regime, trends in yield with sowing date during the study were similar across both seasons.

Plant Measurements and Harvesting

Plants were harvested after >90% of silicles had dried and turned brown and most seed was reddish-brown in color. Dates of harvest ranged from 26 June to 16 July for the earliest to latest seeding date treatments in the first year, and from 30 June to 23 July during the second year of the study. All plots were hand harvested by taking 4.7 m of two center rows for an area of 2.8 m^2. Plants were bagged and dried in a forced air oven at 45°C for 48 to 72 h before threshing and screen cleaning seed. Seed used for harvest calculations was tested for moisture after drying subsamples at 65°C for 48 h and yields were adjusted to a moisture content of 100 g kg^{-1}. Harvest index (HI) was calculated as total dry seed mass divided by total dry biomass.

Plant stands were measured at harvest on 1-m of row randomly selected from one of the center harvest rows of each plot. Within the same row used for stand counts the date was recorded when 50% of the plants showed an open flower. This was accomplished by monitoring plants on a daily basis once flowering began. Growing degree days (GDD) were calculated as: GDD = $\sum (T_{max} + T_{min}/2) - T_{base}$, where T_{max} and T_{min} are daily maximum and minimum air temperature, respectively, and T_{base} is base temperature. Because no published information could be found for GDD calculations for camelina, a base temperature of 4°C was assumed. This is similar to that determined for canola (Vigil et al., 1997), which is a close relative. Air temperature was collected at a weather station adjacent (within 50 m) to the study site. Lodging of plants was measured visually on each plot at harvest using a scale of 0 to 5 with 0 being fully erect and 5 being parallel to the ground.

Seed oil content was measured by pulsed nuclear magnetic resonance (Bruker Minispec pc120, Bruker, The Woodlands, TX) as previously described by Gesch et al. (2005). Approximately 5 to 10 g of seed from each replicated plot (n = 4) was used for analysis. Moisture content was determined according to American Oil Chemist's Society (AOCS) Method 2-75. Each sample was done in duplicate, dried at 130°C for 4 h, and cooled in a desiccator for 15 min. Fatty acid profiles of seed oil were measured by gas chromatography (Hewlett-Packard 5890 Series II, Palo Alto, CA) equipped with a flame-ionization detector and an auto-sampler/injector. Analyses were conducted on a SP-2380 30 m by 0.25 mm i.d. column (Supelco, St. Louis, MO) at a flow rate of 1.1 mL min^{-1} with helium head pressure of 172 kPa (25 psi); split ratio 50:1. Saturated

Table 1. Monthly mean air temperature and precipitation for the 2007–2008 and 2008–2009 seasons.

2007–2008			2008–2009		
Month	Mean air temperature†	Precipitation	Month	Mean air temperature	Precipitation
	°C	mm		°C	mm
September	16.5	115	September	15.6	61
October	10.1	69	October	8.1	104
November	–0.5	0	November	–0.1	47
December	–11.3	3	December	–12.9	3
January	–13.6	1	January	–15.9	1
February	–12.4	0	February	–9.9	10
March	–4.3	10	March	–3.0	74
April	4.5	7	April	5.9	18
May	12.5	48	May	13.8	11
June	18.2	97	June	18.2	41
Total	–	350	Total	–	370

† Air temperature (2-m height) and precipitation were collected at a weather station within 50 m of the field site. Precipitation was monitored throughout the year with an all-weather rain gauge (Met One Model 385, Campbell Scientific, Logan, UT).

C8–C30 fatty acid methyl esters (FAME) provided standards for making fatty acid and by-product assignments. The run temperatures were as follows: 120°C for 3 min; ramp from 120 to 185°C at 25°C min^{-1} and hold for 4.4 min; ramp from 185 to 265°C at 25°C min^{-1} and hold for 0.4 min. Injector and detector temperatures were set at 250°C. Approximately 50 mg of camelina seed was extracted with hexane to make FAMEs using the procedure outline by Forcella et al. (2005).

Statistical Analysis

The experimental data were analyzed by a factorial ANOVA using the General Linear Model Procedure of SAS (SAS for Windows 9.1, SAS Inst., Cary, NC). Data were analyzed separately for each year because of significant treatment by year effects. The main effects analyzed were sowing date, cultivar, and tillage. For the tables shown, the *F*-test probabilities of the main effects are included. Only in the instance of harvest index for the 2008–2009 season was there a significant interaction (sowing date × tillage) therefore, *F*-test probabilities for the two-way and three-way interactions are not shown. Treatment mean comparisons were made by year using least significant differences (LSD) at the $P = 0.05$ level.

RESULTS AND DISCUSSION

Flowering and Plant Density

The overall average air temperature between September and June for both seasons of the experiment was 2°C (Table 1). Total cumulative precipitation was also similar between seasons but the accumulation pattern differed. During the 2008–2009 season between November and March there was 121 mm more precipitation, mainly due to snow, than in 2007–2008 (Table 1). Between May and June of 2007–2008, 93 mm more precipitation was received than in the same time period during 2008–2009 (Table 1).

Fall-seeded camelina reached 50% flowering as early as 22 May in both years (Table 2). Flowering date increased with sowing

Table 2. Effect of sowing date and tillage on timing and accumulated growing degree days (GDD) to 50% flowering in winter camelina. Values except for column averages are individual treatment means of four replicates. For each tillage, values within columns and averages across rows for a given season followed by the same letter are not significantly different at the *P* ≤ 0.05 level.

	2007–2008					2008–2009				
		BSX-WG1		Joelle			BSX—WG1		Joelle	
Tillage†	Sowing date	Flowering date	GDD (°C)	Flowering date	GDD (°C)	Sowing date	Flowering date	GDD (°C)	Flowering date	GDD (°C)
CP	14 Sept.	24 May d	651	26 May d	677	4 Sept.	27 May c	851	1 June c	914
	24 Sept.	27 May c	566	27 May c	566	18 Sept.	2 June b	783	3 June bc	791
	2 Oct.	30 May b	516	3 June b	566	1 Oct.	2 June b	612	6 June b	644
	11 Oct.	4 June a	487	7 June a	525	16 Oct.	10 June a	578	10 June a	578
Avg.		30 May b	555	1 June a	584		3 June b	706	5 June a	732
NT	14 Sept.	22 May d	626	25 May d	669	4 Sept.	22 May c	795	25 May c	833
	24 Sept.	27 May c	566	27 May c	566	18 Sept.	24 May bc	677	28 May bc	722
	2 Oct.	29 May b	503	1 June b	547	1 Oct.	28 May b	551	31 May ab	591
	11 Oct.	2 June a	466	7 June a	525	16 Oct.	4 June a	534	3 June a	522
Avg.		29 May b	540	31 May a	577		27 May b	639	29 May a	667
Effect *P* > *F*‡										
Cv	<0.0001					0.001				
Sd	<0.0001					<0.0001				
Till	0.001					<0.0001				

† Tillages are chisel—plowed (CP) and no—till (NT).

‡ Significance of ***F*** test for the main effects Cv (cultivar), Sd (sowing date), and Till (tillage).

date. However, over both seasons, the difference in number of days to 50% flowering between the first and last sowing date (average of 10 d in 2007–2008 and 11.3 d in 2008–2009) was much fewer than the days between the fall sowing dates themselves (27 d in 2007–2008 and 42 d in 2008–2009). Across sowing dates, more GDD were accumulated during the 2008–2009 season (Table 2) due to both warmer fall and spring temperatures. Despite greater GDD accumulation during the 2008–2009 season, plants reached 50% flowering within a similar period between late May to early June during both seasons. Averaged across all treatments, the difference in 50% flowering date between the two seasons was only 1 d.

The reason for the similarity in 50% flowering dates despite GDD differences between years might be related to photoperiod sensitivity of flowering for the two winter cultivars. Indeed, controlled-environment experiments that were conducted in 2009 showed that Joelle required long-days to trigger flowering (unpublished data). However, it is not fully known whether temperature (i.e., vernalization), in addition to daylength, plays a role in inducing flowering.

During both years of the study, across sowing date and tillage, BSX-WG1 tended to flower 3 d earlier than Joelle (Table 2). Interestingly, tillage also significantly affected flowering date in both years of the study (Table 2). Plants from no-till plots flowered earlier than those grown in chisel plowed soil. This might be related to better winter survivability under no-till, and perhaps a lower degree of freezing-stress, resulting in more rapid spring recovery and growth of plants thus, leading to earlier flowering. Alternatively, the no-till wheat stubble and/or residue cover may have altered the light quality, particularly the red/far red light ratio, perceived by plants. Because winter camelina is photoperiod sensitive, this could have caused the difference in flowering time between the tillage systems. Shading is known to decrease the red/far red light ratio, which can cause plants to flower earlier (Cerdán and Chory, 2003). Also, color of the surface below plants (Kasperbauer, 2000) has been shown to modify the red/far red light ratio, which can alter the morphological development of plants including timing of flowering.

Plant population density during the first season of the study on average was about three to four times greater than that of the second season (Fig. 1). Mean monthly soil temperatures at the 5-cm depth were collected at a weather station adjacent to the study and were not found to greatly differ between winters (data not shown). However, the amount of winter precipitation, primarily snow, between 1 November and 31 March was much greater for the 2008–2009 winter than that for 2007–2008 (i.e., 134 vs. 14 mm, respectively). It was noted that plant survival was lowest in areas where water remained on the surface for several days after snow melt in the spring. It is suggested that waterlogged soil was a bigger detriment to winter camelina survival than freezing stress. Despite this difference, treatment effects were similar across years.

In both years of the study, the no-till soil resulted in greater plant stands than the chisel-plowed soil (Fig. 1A). As hypothesized, the grain stubble in the no-till may have helped trap snow thus, insulating the soil and maintaining a higher temperature than chisel-plowed plots to aid survival of plants. However, as previously stated, survival of plants appeared to be more related to waterlogging than freezing stress.

Although no-till systems prevent soil erosion, they do not necessarily prevent water runoff due to their consolidated surface zone (Lindstrom et al., 1981). Ankeny et al. (1995) studied the effects of tillage on water infiltration at five locations across the Midwest Corn Belt and found that at a Minnesota location no-till soil reduced ponded water infiltration by 33% compared to chisel-plowing. In the present study, the NT plots may have experienced greater water runoff following snow melt, which then collected on the closely adjacent chisel-plowed soil. The surface roughness was greater for the chisel-plowed soil, which may have aided in trapping standing water, thus leading to waterlogging. Alternatively, water infiltration in the NT plots may have been greater earlier in the spring than the CP plots due to their soil profile thawing sooner. Over three winters at the Morris, MN, field site, Sharratt (2002) found that soil covered with 30 and 60 cm tall maize (*Zea mays* L.) stubble thawed as much as 25 d earlier than soil with 0 cm stubble due to insulation caused by snowpack. Indeed, if this phenomenon occurred in the wheat stubble-covered NT plots in our study then snow-melt might have infiltrated sooner, thus resulting in drier surface soil than the CP plots during early spring.

Plant population density did not differ between cultivars the first year of the study (Fig. 1B). However, during the second season, plant stands were greater for Joelle. It is possible that Joelle may have been more resilient than BSX-WG1 to the wetter conditions experienced during the 2008–2009 cropping season, but this needs further research. Sowing date affected plant stand during both years (Fig. 1C). Sowing in early October resulted in greatest stands. Plant stand declined after the early October sowing during the first season but not the second (Fig. 1C), which might have been due to warmer fall temperatures during 2008.

It is important to note that excellent weed control was achieved on plots that had good camelina stand establishment. This might have been due to camelina's vigorous early season growth suppressing and outcompeting weeds. Alternatively, the lack of weed emergence might be related to camelina's known allelopathy (Lovett and Jackson, 1980).

Crop Yields

Sowing date impacted yields and HI during both growing seasons (Tables 3 and 4). The sowing date effect on yield was not as dramatic the first season (Table 3). Nevertheless, similar to plant stand response, seed yield and HI tended to be greatest for the early October sowing followed by that of the mid-October date (Tables 3 and 4). Averaged across all treatments, camelina yields were 193 kg ha^{-1} lower the first year (Table 2) than they were in the second season (Table 4), which was significantly different (P = 0.0002). This might be a consequence of lower soil fertility the first season than the second season when N and P were added in the spring. Furthermore, plant population was much greater the first year (Fig. 1), which may have exacerbated interplant competition for available soil resources (Adams, 1967). Although camelina is generally thought of as a low input crop (Putnam et al., 1993), it does significantly respond to N fertility (Robinson, 1987). However, stress during the reproductive phase caused by waterlogged soil may have contributed more to low yields than fertility during the first year. Canola, a close relative of camelina, is known to be highly sensitive to waterlogging during the spring, which leads to decreased seed yield and oil content (Gutierrez Boem et al., 1996).

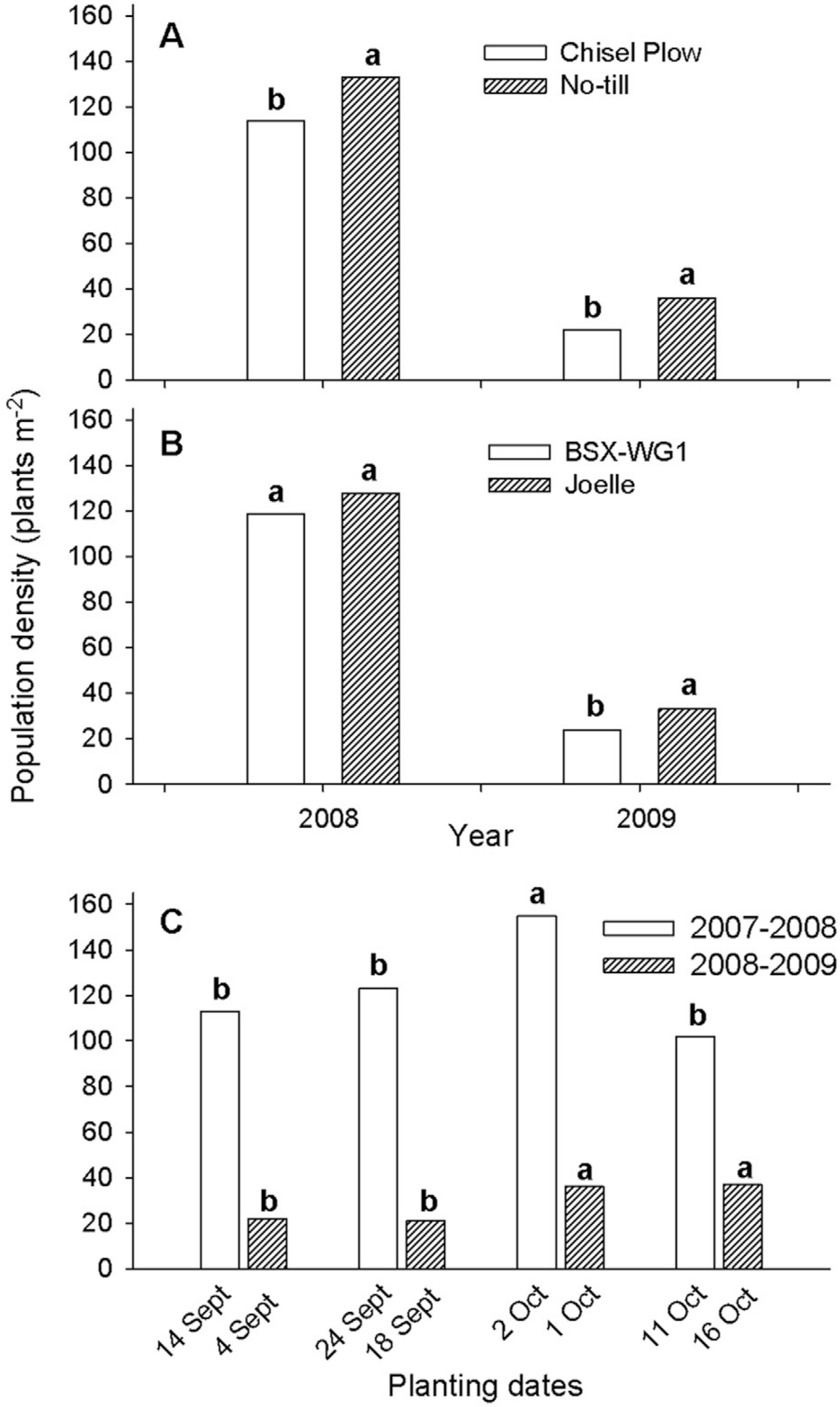

Fig. 1. Plant population density at harvest as effected by (A) tillage, (B) cultivar, and (C) sowing date during the 2007–2008 and 2008–2009 seasons. For each year, bars followed by the same letter are not significantly different at the *P* ≤ 0.05 level.

In our study, between the period of 50% flowering (22 May) to the end of June (when most seed was mature or nearly mature), 115 mm of precipitation fell in 2008 compared to just 46 mm during the same period in 2009. We suggest that camelina's apparent sensitivity to excessive soil moisture deserves further research.

Joelle consistently out-yielded BSX-WG1 across all treatments during both years of the study (Tables 3 and 4). Seed yield of Joelle was 30 and 36% greater than BSX-WG1 during the first and second seasons, respectively. This may have resulted from greater plant stands (Fig. 1B) as a consequence of winter survivability. As a note, during the second year of the study, pictures were taken of 1-m of row from each treatment (data not shown) in the fall and the following spring. The pictures and field observations indicated that Joelle tended to have better survival.

Tillage did not affect seed or biomass yield during the 2007–2008 season (Table 3), but did impact yield in 2008–2009, where the NT system generally resulted in greater yields (Table 4). Interestingly, camelina grown in NT tended to have

Table 3. Yield of BSX—WG1 and Joelle winter camelina for the 2007– 2008 season under chisel—plowed (CP) or no—till (NT). Values except for column averages are individual treatment means of four replicates. For each tillage, values within columns and averages across rows for a given attribute followed by the same letter are not significantly different at the $P \leq 0.05$ level.

Tillage	Sowing date	Seed yield BSX—WG1	Seed yield Joelle	Total biomass BSX—WG1	Total biomass Joelle	Harvest index BSX—WG1	Harvest index Joelle	Lodging† BSX—WG1	Lodging† Joelle
		kg ha^{-1}		kg ha^{-1} DW		kg kg^{-1}			
CP	14 Sept.	311b	490b	1657a	2304a	0.17c	0.20d	2.5a	1.6a
	24 Sept.	388ab	486b	1717a	2114a	0.21b	0.21cd	1.4b	1.4a
	2 Oct.	446a	625a	1821a	2425a	0.22b	0.24b	1.3b	1.0a
	11 Oct.	435ab	607ab	1499a	2166a	0.27a	0.26a	1.5b	1.8a
Avg.		395b	552a	1673b	2253a	0.22a	0.23a	1.7a	1.4a
NT	14 Sept.	467a	441b	2136a	2001a	0.20d	0.20d	0.6a	1.3a
	24 Sept.	425a	569ab	1777ab	2389a	0.22c	0.22c	1.3a	0.9a
	2 Oct.	419a	564ab	1589b	2023a	0.24b	0.26b	1.4a	0.8a
	11 Oct.	492a	614a	1660ab	2098a	0.27a	0.28a	1.1a	0.9a
Avg.		451b	547a	1790b	2128a	0.23a	0.24a	1.1a	0.9a
Effect $P > F$‡									
Cv		<0.0001		0.0003		0.06		0.22	
Sd		0.05		0.76		<0.0001		0.30	
Till		0.38		0.97		0.0002		0.001	

† Lodging was visually scored on a scale of 0 to 5 with 0 being fully erect and 5 being parallel to the ground.

‡ Significance of F test for the main effects Cv (cultivar), Sd (sowing date), and Till (tillage).

a greater HI than for plants grown in CP soil during both years (Tables 3 and 4). This was primarily due to greater seed yield of plants in the NT system. The most likely reason for this, as previously discussed, is that the NT plots tended to be less waterlogged than the CP plots and therefore, plants were likely less stressed and healthier. Alternatively, the earlier flowering of NT plants (Table 2) may have allowed them more time to set and fill seed in early summer when temperatures are mild.

Extensive lodging of camelina was not noted, although there was a tendency for the earliest planting in the CP soil to exhibit the greatest lodging (Tables 3 and 4) and this effect was significant during the second season (Table 4). Averaged across all treatments, lodging was slightly, but significantly greater during the 2008–2009, which may have been related to flooding stress. Others have shown that when compared to other *Brassica* oilseed species, camelina has a relatively low degree of lodging (Putnam et al., 1993; Robinson, 1987).

Oil Content and Fatty Acid Profile

Generally, seed oil content increased with planting date (Table 5). Over both years of the study, Joelle tended to have 20 to 30 g kg^{-1} greater seed oil content than BSX-WG1. Averaged across all treatments, oil content during 2008–2009 was 350 g kg^{-1} as compared to 295 g kg^{-1} during 2007–2008, which was a significant difference ($P < 0.0001$). Like yield, the lower seed oil content during 2007–2008 most likely resulted from stress caused by waterlogged soil.

Table 4. Yield of BSX—WG1 and Joelle winter camelina for the 2008– 2009 season under chisel—plowed (CP) or no—till (NT). Values except for column averages are individual treatment means of four replicates. For each tillage, values within columns and averages across rows for a given attribute followed by the same letter are not significantly different at the $P \leq 0.05$ level.

Tillage	Sowing date	Seed yield BSX—WG1	Seed yield Joelle	Total biomass BSX—WG1	Total biomass Joelle	Harvest index BSX—WG1	Harvest index Joelle	Lodging† BSX—WG1	Lodging† Joelle
		kg ha^{-1}		kg ha^{-1} DW		kg kg^{-1}			
CP	4 Sept.	49b	90c	1262b	1313c	0.04d	0.05c	2.8a	2.5a
	18 Sept.	349b	519b	2070ab	2931b	0.13c	0.15b	2.0ab	2.3ab
	1 Oct.	937a	1317a	3051a	4894a	0.27a	0.25a	2.1ab	1.3b
	16 Oct.	592a	931a	2595a	3884ab	0.20b	0.21ab	1.8b	2.0ab
Avg.		445b	660a	2244b	3255a	0.16a	0.16a	2.2a	2.0a
NT	4 Sept.	460b	612b	1483b	3105a	0.27a	0.18b	2.3a	2.3a
	18 Sept.	537ab	591b	2733a	3094a	0.16b	0.17b	2.3a	2.3a
	1 Oct.	741ab	1163a	3149a	3688a	0.21ab	0.27a	2.0a	1.5a
	16 Oct.	910a	1221a	3128a	3961a	0.27a	0.29a	1.8a	1.5a
Avg.		612b	829a	2623b	3462a	0.23a	0.23a	2.1a	1.9a
Effect $P > F$‡									
Cv		0.007		0.0004		0.99		0.35	
Sd		<0.0001		<0.0001		<0.0001		0.01	
Till		0.04		0.23		0.0001		0.49	

† Lodging was visually scored on a scale of 0 to 5 with 0 being fully erect and 5 being parallel to the ground.

‡ Significance of F test for the main effects Cv (cultivar), Sd (sowing date), and Till (tillage).

Table 5. Total seed oil content for winter camelina cultivars BSX—WG1 and Joelle grown in chisel—plowed and no—till soil during two seasons. Values except for column averages are individual treatment means of four replicates. Values within columns and averages across rows followed by the same letter are not significantly different at the $P \leq 0.05$ level.

Tillage	Sowing date	2007–2008 Oil content		Tillage	Sowing date	2008–2009 Oil content	
		BSX—WG1	Joelle			BSX—WG1	Joelle
		g kg^{-1}				g kg^{-1}	
CP	14 Sept.	271b	303ab	CP	4 Sept.	265b	297b
	24 Sept.	289a	304ab		18 Sept.	292ab	312ab
	2 Oct.	286ab	296b		1 Oct.	306a	334a
	11 Oct.	299a	313a		16 Oct.	313a	332a
Avg.		286b	304a			294b	319a
NT	14 Sept.	286a	294b	NT	4 Sept.	341b	367b
	24 Sept.	282a	299b		18 Sept.	365b	384b
	2 Oct.	282a	307ab		1 Oct.	369ab	391ab
	11 Oct.	293a	315a		16 Oct.	397a	419a
Avg.		286b	304a			368b	390a
Effect $P > F$†				Effect $P > F$			
Cv		<0.0001		Cv		0.0004	
Sd		0.002		Sd		<0.0001	
Till		0.81		Till		<0.0001	

† Significance of F test for the main effects Cv (cultivar), Sd (sowing date), and Till (tillage).

Although tillage did not affect seed oil content in 2007–2008, it did have a significant impact the second year, where average oil content was 70 g kg^{-1} greater for the NT system ($P < 0.0001$). The greater seed oil content for NT plants probably resulted from either better overwintering survival leading to healthier plants, or more likely, because of less watterlogging damage than those in the CP system. The CP system did suffer from considerably more waterlogging than the NT system during both seasons. Alternatively, the higher oil content could be related to earlier flowering in the NT system, perhaps extending the period for oil synthesis and seed filling.

Table 6. Contents of prominent fatty acids (% of total oil) in the seed oil of winter camelina grown under no—till during the 2007–2008 season. Values except for column averages are individual treatment means of four replicates. Values within columns followed by the same letter are not significantly different at the $P \leq 0.05$ level. The letters x and y are used to compare averages between cultivars for a given FA.

Cultivar	Sowing date	Oleic 18:1	Linoleic 18:2	Linolenic 18:3	Eicosenoic 20:1
BSX—WG1			%		
	14 Sept.	13.7a	21.4a	32.1b	11.6a
	24 Sept.	13.5a	21.3a	32.3b	12.0a
	2 Oct.	14.0a	20.8a	35.5a	11.5a
	11 Oct.	13.8a	21.4a	32.8b	12.3a
Avg.		13.7y	21.2x	33.2y	11.9x
Joelle					
	14 Sept.	14.9bc	20.2a	35.1a	11.5a
	24 Sept.	14.5c	20.0a	35.2a	11.8a
	2 Oct.	15.0b	19.2a	36.0a	12.0a
	11 Oct.	15.6a	19.9a	35.4a	12.4a
Avg.		15.0x	19.8y	35.4x	11.9x
Effect $P > F$†					
Cv		<0.0001	0.0004	0.002	0.85
Sd		0.01	0.40	0.09	0.41
Till		0.43	0.39	0.47	0.0002

† Significance of F test for the main effects Cv (cultivar), Sd (sowing date), and Till (tillage).

Neither sowing date nor tillage had a significant effect on the content of fatty acids with the exception of eicosenoic acid, which on average was 0.9% greater for the NT (11.9%) than the CP system (11.0%) (Table 6). There was a year effect, but primarily it was due to a slightly higher C18:3 content (3% greater) of seed during the second year of the study. Unsaturation of fatty acids does tend to increase with decreasing temperature during seed and oil development (Tremollieres et al., 1982). However, the mean monthly temperatures of May and June, when plants were flowering and setting seed, were similar between years in this study. Fatty acid profile did differ by cultivar with Joelle having slightly higher C18:1 and C18:3 contents and lower C18:2 content than BSX-WG1 (Table 6). Other studies have also shown that although statistically significant, differences in the content of individual fatty acids tends to be relatively small among different genotypes (Gugel and Falk, 2006) and even across environments (Zubr and Matthäus, 2002).

CONCLUSIONS

This study has shown that camelina can be successfully grown as a winter annual crop in the northern Corn Belt and further supports the notion that it can be done with minimal agricultural inputs (i.e., produced in a no-till system without herbicide use). Our results indicate that fall seeding in early to mid-October is best to optimize seed yield and oil content in west central Minnesota. Although seed yield and oil content did not consistently differ between tillage systems, seeding camelina into NT wheat stubble generally resulted in better plant survival and consequently greater population density at harvest than the CP system, but not always greater yields. Furthermore, the NT system led to earlier flowering of plants. This could have important implications for hastening maturation and hence harvest of camelina, which might allow for the potential to produce a second short-season food or forage crop.

ACKNOWLEDGMENTS

The authors wish to thank Joe Boots for his expert field assistance and Linda Manthey for oil and fatty acid analysis.

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