Enhanced Efficiency Nitrogen Fertilizer Effect on Camelina Production under Conventional and Conservation Tillage Practices

Reza Keshavarz Afshar¹, Yesuf Assen Mohammed¹, and Chengci Chen^{1*}

¹Eastern Agricultural Research Center, Montana State University

*corresponding author: cchen@montana.edu

Abstract

Camelina (*Camelina sativa*) is a promising biofuel feedstock to fill the fallow period in dryland wheat (*Triticum aestivum*) -fallow cropping system of the U.S Northern Great Plains (NGP). Responses of camelina to tillage system (conventional tillage [CT] and no-till [NT]), nitrogen (N) rate (0, 45, 90 kg ha⁻¹), and nitrogen source (urea and an Enhanced Efficiency Nitrogen fertilizer [EENF] containing urease and nitrification inhibitors) were evaluated in a 2-yr (2013-2014) field experiment in a dryland farming system of central Montana. Grain yield, biomass, oil content, and oil yield of camelina displayed significant first-order effects of tillage, N rate, and N source when averaged across each of the other factors, but interaction effects were not significant. Camelina tended to yield greater in CT than NT by about 26%. Application of EENF significantly increased grain yield when compared with U, which was more pronounced under CT. Dose response of camelina grain yield, biomass, and grain protein to N rate in the range of 0 to 90 kg ha⁻¹ was linear, whereas N fertilization showed a detrimental effect on oil accumulation in seeds. Despite a linear response, grain produced in response to application of N in addition to 45 kg ha⁻¹, was very small. Although oil content declined in response to N application, oil yield (kg ha⁻¹), which is the most important criteria in seed-oil derived biofeedstock, positively responded to N application. Our results clearly demonstrated the need for further research to

optimize management strategies for successful camelina production under NT system. Our results also indicated potential of EENF in enhancing the yield of camelina especially under CT system. Irrespective to tillage system and source of N, application of 90 kg N ha⁻¹ (minus soil mineral N) led to highest yield of camelina in this environment, but yield gain in response to N application further than 45 kg ha⁻¹ was very small.

Keywords: Biofuel; No-tillage; Nitrogen Fertilizers; Urease and nitrification inhibitors.

1

1. INTRODUCTION

Camelina has shown considerable agronomic and ecological potential to replace fallow in the wheat-fallow predominant cropping system in the U.S. NGP (McVay and Lamb, 2008; Chen et al., 2015). Our previous studies have shown that due to relatively high production cost and low yield of the crop, replacing fallow with camelina is not yet economically feasible in the NGP (Chen et al., 2015). It was shown that for farmers to adopt camelina in their cropping systems, higher yield and/or lower production cost is essential (Chen et al., 2015).

In our previous economic analyses, we showed that N has the biggest share of production costs in camelina production when N was applied at a rate of 75 kg ha⁻¹ (Chen et al., 2015). Moreover, analysis of on-farm energy flow revealed that optimization of N fertilization has the highest

¹ **Abbreviations:** EENF, Enhanced Efficiency Nitrogen fertilizer containing urease and nitrification inhibitors; CT, conventional tillage; NT, no-tillage; N, nitrogen; NGP, U.S. Northern Great Plains; NUE, nitrogen use efficiency; U, urea fertilizer; SU, SuperU.

priority to enhance energy use efficiency and reduce the energy footprint of camelina in this environment (Keshavarz Afshar et al., 2015a; Keshavarz Afshar and Chen, 2015). Since, excessive N applications are undesirable, from both economic and environmental standpoints (Spargo et al., 2008), improving N fertilization strategy is paramount to both agronomic viability and environmental health.

Nitrogen fertilization greatly interacts with soil management, including tillage, in different ways (Halvorson et al., 2006; López-Bellido and López-Bellido, 2001). Generally, the crop's response to N in a dryland system depends greatly on moisture availability (Angás et al., 2006). Since tillage affects soil moisture, it is expected to influence crop's response to N as well. Moreover, tillage affects N dynamics in the soil through altering soil structure and aeration (Karlen et al., 1998), as well as soil organic matter and crop residue mineralization (Wienhold et al., 1999). Thus, it is expected that the response of a crop to N fertilizer varies from conventional tillage (CT) to no-till (NT). Extensive research efforts have focused on the response of major agronomic crops to N fertilizer under NT vs. CT (Camara et al., 2003; Kelley and Sweeney, 2005; Rieger et al., 2008), whereas limited information exists regarding the response of camelina to N fertilization under different tillage systems. Rieger et al. (2008) reported that wheat grain yield was lower under NT compared to CT, which was not altered by application of N fertilizer. Halvorson et al. (1999) conducted a 12-year study to determine winter wheat response to tillage system and N fertilizer rate in a dryland system of the NGP. They reported wheat grain yield was greater under NT (2022 kg ha⁻¹) than that under CT (1801 kg ha⁻¹) and increasing N rate from 34 kg N ha⁻¹ to 67 kg N ha⁻¹ increased grain production from 1844 to 1953 kg ha⁻¹. They pointed out that maintaining crop residue on the soil surface in NT system trapped winter snow, which contributed to higher yield of wheat in NT than in CT. Similarly, a lower yield of durum wheat

under reduced tillage has been reported when no N fertilizer was applied, whereas application of 50 to 100 kg N ha⁻¹ alleviated the deleterious effect of reduce tillage on crop yield (De Giorgio et al. 2004). In some other studies, identical responses of crop to N fertilizer rate have been documented, regardless of the tillage method (Riley, 1998).

In addition to rate of N, source of N also plays an important role in N management. Urea is the principal source of N fertilizer worldwide. Previous studies in Montana have shown that N loss through ammonia (NH₃) volatilization can exceed 40% when urea is broadcasted on the soil surface (Engel et al., 2011). It has been reported that Enhanced Efficiency Nitrogen Fertilizers that contain urease inhibitors and/or nitrification inhibitors have potential to mitigate N loss, mostly through lowering NH₃ volatilization and N₂O emission (Thapa et al., 2015; Zaman et al., 2008). Nevertheless, discrepancies have been reported with respect to the influence of EENF on crop yields; some researchers reported yield advantages (Dawar et al., 2012; Abalos et al. 2014; Kyveryga and Blackmer, 2014) whereas others found no effects (McKenzie et al., 2010; Franzen et al., 2011; Sistani et al., 2011; Thapa et al., 2015). Since the potential of NH₃ volatilization in central Montana is abundant, the likelihood to obtain positive influence of EENF on crop yield is relatively high, which requires more research to determine.

In the current study, we aimed to determine the N-dose response of camelina under CT and NT on a dryland farming system of central Montana. We hypothesized that the optimum N rate for wheat-camelina rotation would be affected by tillage system. We also examined if replacing urea with an EENF could enhance camelina grain yield and oil production.

2. MATERIALS AND METHODS

2.1. Experimental site

Field trials (2013-2014) were conducted at the Central Agricultural Research Center (47° 03' N, 109°57'W; 1400 m elevation) near Moccasin, Montana. Long-term average monthly air temperature and precipitation, which were recorded at the experimental site as well as the monthly precipitation and average temperature during the study are presented in Fig. 1. The typical frost-free period in this location is 110 d.

“Please insert Fig 1 here”

Soil at the site is classified as a Judith clay loam (fine –loamy, carbonatic, frigid Typic Calciustolls) and its water holding capacity is limited by gravel content and shallow soil profile. General soil characteristics are shown in Table 1.

“Please insert Table 1 here”

2.2. Experimental details

The experiment consisted of two tillage systems (CT and NT), three rates of nitrogen (0, 45, 90 kg N ha⁻¹), and two sources of N (urea and an EENF named SuperU [SU]). SuperU® (46% N) is a urea fertilizer stabilized with both, urease inhibitor N-(n-butyl)-thiophosphoric triamide and the nitrification inhibitor dicyandiamide [DCD] (Koch Industries, Inc., KS, USA). Experimental plots (15.2 m long and 3.7 m wide) were laid out in a split-split plot pattern based on a randomized complete block design with four replicates. Tillage system, N rate, and N source were assigned to the main plots, sub-plots, and sub-sub plots, respectively. The experimental units had a history of the same tillage system (CT or NT) for at least five years.

2.3. Agronomy

Conventional tillage consisted of two passes of a sweep cultivator, whereas in the NT system, seeds were directly sown into the previous crop (winter wheat) stubble. Camelina seeds (cv. Blaine Creek) were sown between late March to early April using a plot air drill at 0.3 m row width and at the rate of 5.6 kg ha⁻¹. Nitrogen fertilizer (either urea or EENF) was broadcasted on soil surface at camelina rosette stage. Based on soil test results, no PKS fertilizers were used.

Weed management differed between the two tillage systems. In both systems, one burn-down herbicide (1.12 L a.i ha⁻¹ glyphosate) was applied in early September. In NT system, however, one additional spray of glyphosate (1.12 L a.i ha⁻¹) was used in early spring (before seeding). After that, no other weed control was undertaken.

2.4. Data Collection

The grain harvest was done using a Wintersteiger plot combine (Wintersteiger Inc., Salt Lake City, UT) in late July to early August. After harvesting, grains were threshed, cleaned, and weighed. Grain yield reported herein is adjusted to 6% (w/w) moisture content. At the time of maturity, plants were sampled from 1m² of each plot to determine biomass. Harvest index (HI) is the ratio of grain yield to total biomass. Nitrogen concentration in grain was determined using a combustion method following the procedure described by Chen et al. (2011). Grain oil content was determined using a MARAN Ultra System NMR (Oxford Instrument, Abington, UK). Oil yield (kg ha⁻¹) was calculated as the function of oil content and grain yield. Oil and N content are reported on a dry weight basis as a percent of whole grain.

2.5. Data Analysis

Data were analyzed using PROC Mixed (method= type3) of SAS (version 9.3). There is a discussion among researchers to either consider year as a fixed or random effect in multi-year

agronomic studies. We ran statistical models for both assumptions. The results were identical, therefore, we decided to present results assuming year, block, and block(year) as random effects while tillage, N source and N rate were used as fixed effects. Contrast statements were used to test for linear and quadratic responses to N rate (main effects and interactions), and regression equations describing the relationship between the dependent variables and N rate were fitted based on the nature of the response (O'Donovan et al., 2011). To calculate LSD values (at $P < 0.05$) when F test rejected the null hypothesis, we used SAS macro %MULT (Piepho, 2012). We followed guidelines provided by McIntosh (2015) to create a SIMPLE (Simple, Informative, Meaningful, Powerful, Logical, and Effective) ANOVA table, which includes sources of variation, effect type, degrees of freedom, F values, and significance level for fixed effects and mean squares (MS) for random effects.

Also, to better understand the response of crop to N fertilizer, we ran a simple economic analysis assuming that all fixed/ownership as well as variable costs are fixed except that of N fertilizer. For this purpose, the price of urea was considered US \$0.88 kg⁻¹ (average price for Montana) and the price of SU was considered 20% higher than U. Price of camelina grain was considered as \$0.20 kg⁻¹ (average price of camelina in the last five years).

3. Results

Results of the statistical analysis are shown in Table 2. The main effects of tillage, N source, and N rate were highly significant on grain yield, biomass, and oil yield, whereas grain oil and protein content only responded to N rate. No significant interactive effects were found among experimental factors (except for Till $\times$ N source on grain yield) (Table 2). These results show that each factor (tillage, N source, and N rate) affected camelina independently and irrespective

to the levels of the other factors. Therefore, we will focus on presenting main effects of tillage, N source and N rate on camelina dependent variables.

“Please insert Table 2 here”

3.1. Effect of tillage system

Tillage system highly ($P \leq 0.01$) influenced camelina grain yield, biomass, and oil yield (Table 2). Our results indicated that camelina had more favorable growing conditions under CT, which was reflected by 26 and 20% greater grain and biomass yields in this system compared to NT, respectively (Table 3). No changes were observed with respect to the effect of tillage on grain oil and protein content. Nonetheless, due to greater grain yield, oil yield (kg oil ha^{-1}) was also significantly higher in CT than that in NT.

3.2. Effect of nitrogen source

Source of N had a significant effect on camelina grain, biomass and oil yield, but did not influence oil and protein (Table 2). The response of camelina to N source with respect to grain yield differed between tillage systems (Fig. 2).

“Please insert Fig. 2 here”

In CT system, application of SU produced a significantly greater yield than U. However, in NT system, grain yield did not differ between two sources of N. Regardless of the tillage system, camelina tended to produce greater biomass and oil yield when treated with SU compared with U (Table 3). Averaged over tillage systems and N rates, grain yield, biomass, and oil yield of camelina was 32, 16, and 29% higher when treated with SU compared with U (Table 3). The HI was also significantly increased by SU treatment

Application of 45 and 90 kg of U would cost \$39.6 and \$79.2 ha⁻¹, respectively. Replacing U with SU would need an additional of \$7.92 and \$15.84 ha⁻¹, when N is applied at the rate of 45 and 90 kg ha⁻¹, respectively. On the other hand, application of SU out yielded U by 231 kg ha⁻¹ (averaged over the years, tillage systems, and N rates). Assuming \$0.22 kg⁻¹ of camelina, this advantage equals to \$50.82 ha⁻¹, which completely offset SU additional cost of \$7-15 ha⁻¹.

“Please insert Table 3 here”

3.3. Effect of nitrogen rate

Except HI, all camelina depended variables were highly influenced by N rate (in the range of 0 to 90 kg ha⁻¹) (Table 2). Camelina grain yield and biomass followed a linear increasing trend with increased N rate (Fig. 3). As mentioned previously, camelina responded to N rate regardless of the tillage system or source of N. Application of 45 and 90 kg N ha⁻¹ enhanced grain yield by 31 and 54%, respectively, compared to yield of 643 kg ha⁻¹ in control plots. As seen in Fig. 3a, despite a linear response to the increasing rate of N, the yield response to N application further than 45 kg ha⁻¹ was very small and insignificant. In fact, yield difference between 45 and 90 kg N ha⁻¹ treatments was 133 kg ha⁻¹ (averaged over the years, tillage systems and sources of N), which equals to US \$29.2 and is lower than the fertilizer cost of \$39.60. The regression line for biomass response to N was sharper than that of grain yield (slope 8.7 vs. 3.8), however, the difference was not large enough to hinder HI (Table 3). In contrast to grain yield and grain protein, oil content tended to decline with nitrogen fertilization and a negative linear regression was well fitted between oil content and nitrogen rate (Fig. 3). Despite the detrimental effect of nitrogen fertilizer on oil accumulation in grains, oil yield (kg oil ha⁻¹) responded positively to N fertilization, due to its greater influence on grain yield rather than that on oil content.

“Please insert Fig. 3 here”

4. Discussion

4.1. Conventional tillage vs. no-till

The results of the current study showed 26% greater yield for camelina under CT compared with that under NT, which was observed regardless of the changes in nitrogen fertilization (rate and/or source). Discrepancies have been reported in the literature regarding the responses of various crops to tillage system. While lower yields under NT compared to CT have been reported (López-Bellido and López-Bellido, 2001; Halvorson et al., 2006; Rieger et al., 2008), some other researchers found yield increment when NT was adopted (De Vita et al. 2007; Fernández-Ugalde et al., 2009). The lower yield of camelina under NT was in contrast to general expectations for this semi-arid environment (specifically, due to an expected better soil moisture availability under NT). Several assumptions can be made to explain yield decline following a conversion to NT. Considering the condition of the current study, the followings seem paramount to explain our results:

1) The environmental condition greatly interacts with tillage system (Pittelkow et al., 2015). Removal of residues from the soil surface in CT exposes more soil to solar radiation, and decreases soil albedo, which increases soil temperatures. This is while the presence of residue on the soil surface in NT lowers soil temperature, which could cause a delay in seed germination, seedling emergence, and ultimately the rate of crop development (Giller et al., 2009). When typical freezing winters and cold springs in central Montana are taken into account, the better performance of camelina in CT could be partly explained by this assumption.

2) Camelina is a relatively new crop to North America. Best agronomic management practices for this crop are not fully explored yet. Specifically, chemical herbicides have not been registered for weed management in this crop (except Poast herbicide). Higher weed pressure in NT than CT is

typically reported (Giller et al., 2009; Farooq et al., 2011). Considering the limitations in weed chemical management, weeds could be more problematic in NT. Typically, we noticed greater pressure of weeds, especially grass weeds like cheatgrass (*Bromus tectorum*), under NT compared to CT especially when camelina was rotated with a wheat crop. Similarly, Camara et al. (2003) reported that despite beneficial effects on soil properties, conservation tillage has tended to be less productive for wheat production in eastern Oregon than moldboard plowing, which they contributed to lack of downy brome weed control in the conservation tillage systems.

3) A certain level of experience is needed to successfully establish a no-till crop. Biophysical factors alongside lack of knowledge of appropriate equipment, soil conditions, seeding techniques, etc. can affect the success of NT adoption. In fact, NT often requires a number of changes to a system, such as an appropriate straw management, precise seeding equipment, sufficient horsepower of the tractor, optimized N management, appropriate approach for P and K application, appropriate herbicide availability, and sometimes a more appropriate cultivars for NT condition (Derpsch et al., 2014). Therefore, more targeted research and extension efforts are needed to guarantee equal or higher yields in NT than with conventional tillage systems.

After all, when comparing NT to CT, other services and benefits that NT offers to the agroecosystems such as soil protection against erosion, more C sequestration in soil, lower off-farm energy use, and less greenhouse gas emissions (Keshavarz Afshar et al., 2015a) should be considered.

4.2. Urea vs. EENF

According to the results of this study, SuperU outperformed regular urea in camelina production, especially when the CT system was implemented. Our results are in line with a conclusion made

by Abalos et al. (2014) who concluded a 7.5% yield benefit from EENF after conducting a meta-analysis on data of 27 field studies. Our result, however, does not agree with the findings by McKenzie et al. (2010), Thapa et al. (2015), and Sistani et al. (2011), who reported that EENF (urease inhibitor or NBPT containing fertilizers) had no influence on grain yield and protein of wheat in rain-fed conditions. The beneficial effects of EENF on crop yield greatly depend on the environmental condition. One ecological advantage of EENF is that they release N gradually, which provides a better synchrony between N release and plant capacity to uptake it, which ultimately minimizes the chance of N to be lost. Our previous studies showed that SU creates a wider window for N to be entered into the soil by the means of rainfall and depending on the environmental condition, cumulative NH_3 volatilization could be reduced by more than 50% when U was replaced with SU (Keshavarz Afshar et al., 2016). Mitigation of NH_3 volatilization, which has been shown to exceed 45% of the N fertilizer in this dryland farming system can be translated into greater yield and higher NUE.

4.3. Nitrogen rate

Camelina grain yield, biomass, and grain protein content responded linearly to the increasing rate of N (Fig. 2). Therefore, the highest rate of N (90 kg ha^{-1}) provided the highest yield, regardless of the tillage type or source of N. However, despite a linear response to increased rate of N, the yield difference between 45 and 90 kg N ha^{-1} treatment was not statistically significant (Fig. 3). Therefore, although application of N in addition to 45 kg ha^{-1} increased camelina grain yield slightly, an economic analysis showed this increase was not justified considering price of the fertilizer. Consistently, Mohammed et al., (2016) found from a trend analysis that application of 60 kg N ha^{-1} produced the agronomic maximum seed and oil yield of camelina in dryland central Montana. Other researchers also reported that camelina nitrogen requirement ranged from 78 to-

100 kg ha⁻¹, depending on the soil fertility, the residual level of nutrients, and weather conditions (Zubr, 1997; McVay and Lamb, 2008; Jackson, 2008).

While application of N had a positive influence on grain yield and protein, grain oil content was negatively influenced. Generally speaking, application of nitrogen fertilizer lowers oil content in favor of protein content in oilseed crops (Keshavarz Afshar et al., 2015b). As hypothesized by Rathke et al. (2006), the inverse relationship between protein and oil occurs due to the lower levels of carbohydrate in protein than in oil, thus; an increased supply of N stimulates protein synthesis at the expense of fatty acid synthesis in most oilseed crops. The negative correlation found between oil and N content in camelina is consistent with reports by other researchers (Urbaniak et al. 2008; Malhi et al., 2014). Since oil is the main product of camelina, tradeoffs between grain yield and oil content in response to N fertilizer should be considered. Oil yield has more importance than oil content in feedstock production for seed oil-derived biofuel (Gesch and Cermak, 2011), which responded well to N rate increase from 0 to 90 kg ha⁻¹ in the current study.

CONCLUSION

This study has demonstrated that:

- Camelina yielded less when NT was adopted. More efforts are needed to optimize agronomic practices when NT is adopted for camelina production in this dryland ecosystem.
- Application of EENF (SuperU in this study) produced a significantly higher yield than regular U. This increase, was also economically feasible.

- Camelina linearly responded to N rate from 0 to 90 kg ha⁻¹. Application of N in addition to 45 kg ha⁻¹, however, increased yield very slightly which was not economically justified. Neither tillage system, nor source of N influenced camelina yield response to N rate.

Acknowledgement

We acknowledge the funding support from the Montana Agricultural Experiment Station, and USDA-NIFA BRDI grant No. 2012-10006-20230.

References

- Abalos, D., Jeffery, S., Sanz-Cobena, A., Guardia, G., Vallejo, A., 2014. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. *Agric, Ecosyst. Environ.* 189, 136-144.
- Angás, P., Lampurlanés, J., Cantero-Martínez, C., 2006. Tillage and N fertilization: effects on N dynamics and barley yield under semiarid Mediterranean conditions. *Soil Till. Res.* 87, 59-71.
- Camara, K. M., Payne, W. A., Rasmussen, P. E., 2003. Long-term effects of tillage, nitrogen, and rainfall on winter wheat yields in the Pacific Northwest. *Agron. J.* 95, 828-835.
- Chen, C., Bekkerman, A., Keshavarz Afshar, R., Neill, K., 2015. Intensification of Dryland Cropping Systems for Bio-feedstock Production: Evaluation of Agronomic and Economic Benefits of *Camelina sativa*. *Ind. Crop. Prod.* 71, 114-121.

- Chen, C., Han, G., He, H., Westcott, M., 2011. Yield, protein and remobilization of water soluble carbohydrate and nitrogen of three spring wheat cultivars as influenced by nitrogen input. *Agron. J.* 103, 786-795. Doi:10.2134/agronj2010.0424
- Dawar, K., Zaman, M., Rowarth, J.S., Turnbull, M.H., 2012. Applying urea with urease inhibitor (N-(n-butyl) thiophosphoric triamide) in fine particle application improves nitrogen uptake in ryegrass (*Lolium perenne* L.). *Soil Sci. Plant Nutr.* 58, 309–318.
- De Giorgio, D., Convertini, G. Fornaro, F., 2004. Soil tillage and nitrogen fertilization effects on yield and quality of durum wheat in rotation with broad bean in southern Italy. *Proc. 15th Int. Symp. of International Scientific Centre of Fertilizers*, pp. 163–174.
- De Vita, P., Di Paolo, E., Fecondo, G., Di Fonzo, N., Pisante, M., 2007. No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. *Soil Till. Res.* 92, 69-78.
- Derpsch, R., Franzluebbers, A.J., Duiker, S.W., Reicosky, D.C., Koeller, K., Friedrich, T., ... Weiss, K., 2014. Why do we need to standardize no-tillage research?. *Soil Till. Res.* 137, 16-22.
- Engel, R., Jones C., R. Wallander., 2011. Ammonia volatilization from urea and mitigation by NBPT following surface application to clod soils. *Soil Sci. Soc. Am. J.* 75, 2348-2357.
- Farooq, M., Flower, K.C., Jabran, K., Wahid, A., Siddique, K.H. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil Till. Res.* 117, 172-183.

- Fernández-Ugalde, O., Virto, I., Bescansa, P., Imaz, M.J., Enrique, A., Karlen, D.L., 2009. No-tillage improvement of soil physical quality in calcareous, degradation-prone, semiarid soils. *Soil Till. Res.* 106, 29-35.
- Franzen, D., Goos, R.J., Norman, R.J., Walker, T.W., Roberts, T.L., Slaton, N.A., ... Lukach, J., 2011. Field and laboratory studies comparing Nutrisphere-nitrogen urea with urea in North Dakota, Arkansas, and Mississippi. *J. Plant Nutr.* 34, 1198-1222.
- Gesch, R.W., Cermak, S., 2011. Sowing date and tillage effects on fall-seeded camelina in the northern Corn Belt. *Agron. J.* 103, 980–987.
- Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crop. Res.* 114, 23–34
- Halvorson, A.D., Black, A.L., Krupinsky, J.M., Merrill, S.D., 1999. Dryland winter wheat response to tillage and nitrogen within an annual cropping system. *Agron. J.* 91, 702-707.
- Halvorson, A.D., Mosier, A.R., Reule, C.A., Bausch, W.C., 2006. Nitrogen and tillage effects on irrigated continuous corn yields. *Agron. J.* 98, 63-71.
- Jackson, G.J., 2008. Response of camelina to nitrogen, phosphorus, and sulfur. *Fertilizer Facts*. Montana State Univ., Ext. Serv. Available at <http://landresources.montana.edu/fertilizerfacts/documents/FF49CamelinaNPS.pdf> (accessed 11/3/2015).
- Karlen, D.L., Kumar, A., Kanwar, R.S., Cambardella, C.A., Colvin, T.S., 1998. Tillage system effects on 15-year carbon-based and simulated N budgets in a tile-drained Iowa field. *Soil Till. Res.* 48, 155-165.

- Kelley, K.W., Sweeney, D.W., 2005. Tillage and urea ammonium nitrate fertilizer rate and placement affects winter wheat following grain sorghum and soybean. *Agron. J.* 97, 690-697.
- Keshavarz Afshar, R., Lin, R., Mohammed, Y., Chen, C. 2016. Mitigation of Ammonia Emission Associated with Surface-Applied Nitrogen Fertilizer in a dryland farming system: Field and Laboratory Investigations. *J. Clean. Prod.* Accepted.
- Keshavarz-Afshar, R, Mohammed, Y., Chen, C., 2015a. Energy balance and greenhouse gas emissions of dryland camelina as influenced by tillage and nitrogen. *Energy*, 91, 1057-1063.
- Keshavarz Afshar, R., Chaichi, M.R., Rezaei, K., Asareh, M.H., Karimi, M., Hashemi, M. (2015b). Irrigation regime and organic fertilizers influence on oil content and fatty acid composition of milk thistle seeds. *Agron. J.* 107, 187-194.
- Keshavarz-Afshar, R, Chen, C., 2015. Intensification of dryland cropping systems for bio-feedstock production: energy analysis of camelina. *BioEnergy Res.* 8, 1877-1884.
- Kyveryga, P.M., Blackmer, T. M., 2014. Probability of profitable yield response to nitrification inhibitor used with liquid swine manure on corn. *Precision Agric.* 15, 133–146
- López-Bellido, R.J., López-Bellido, L., 2001. Efficiency of nitrogen in wheat under Mediterranean conditions: effect of tillage, crop rotation and N fertilization. *Field Crop. Res.* 71, 31-46.
- Malhi, S.S., Johnson, E.N., Hall, L.M., May, W.E., Phelps, S., Nybo, B., 2014. Effect of nitrogen fertilizer application on seed yield, N uptake, and seed quality of *Camelina sativa*. *Can. J. Soil Sci.* 94, 35-47.
- McIntosh, M. S., 2015. Can Analysis of Variance Be More Significant?. *Agron. J.* 107, 706-717.

- McKenzie, R.H., Middleton, A.B., Pfiffner, P.G., Bremer, E., 2010. Evaluation of polymer-coated urea and urease inhibitor for winter wheat in southern Alberta. *Agron. J.* 102, 1210–1216. doi:10.2134/ agronj2009.0194
- McVay, K.A., Lamb, P.F. 2008. Camelina Production in Montana. A self-learning resource from MSU extension. Available at <http://msuextension.org/publications/AgandNaturalResources/MT200701AG.pdf>; Accessed Aug. 9, 2012.
- Mohammed, Y., Keshavarz Afshar, R., Chen, C. 2016. Nutrient requirements of camelina (*Camelina sativa* L. Crantz) for biodiesel feedstock in central Montana. *Agron. J.* Accepted.
- O'Donovan, J.T., Turkington, T. K., Edney, M. J., Clayton, G. W., McKenzie, R. H., Juskiw, P. E., Lafond, G. P., et al., 2011. Seeding rate, nitrogen rate, and cultivar effects on malting barley production." *Agron. J.* 103, 709-716.
- Piepho, H.P., 2012. A SAS macro for generating letter displays of pairwise mean comparisons. *C.B.C.S.* 7, 4-13.
- Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., Van Groenigen, K.J., Lee, J., ... Van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. *Field Crop Res.* 183, 156-168.
- Rathke, G.W., Behrens, T., Diepenbrock, W., 2006. Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (*Brassica napus* L.): a review. *Agric. Ecosyst. Environ.* 117, 80-108.

- Rieger, S., Richner, W., Streit, B., Frossard, E., Liedgens, M., 2008. Growth, yield, and yield components of winter wheat and the effects of tillage intensity, preceding crops, and N fertilisation. *Eur. J. Agron.* 28, 405-411.
- Riley, H.C.F., 1998. Soil mineral-N and N-fertilizer requirements of spring cereals in two long-term tillage trials on loam soil in southeast Norway. *Soil Till. Res.* 48, 265–274.
- Schillinger, W.F., Wysocki, D.J., Chastain, T.G., Guy, S.O., Karow, R.S., 2012. Camelina: Planting date and method effects on stand establishment and seed yield. *Field Crop. Res.* 130, 138-144.
- Sistani, K.R., Jn-Baptiste, M., Lovanh, N., Cook, K.L., 2011. Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers. *J. Environ. Qual.* 40, 1797–1805. doi:10.2134/jeq2011.0197
- Spargo, J.T., Alley, M.M., Follett, R.F., Wallace, J.V., 2008. Soil nitrogen conservation with continuous no-till management. *Nutr. Cycl. Agroecosys.* 82, 283-297.
- Thapa, R., Chatterjee, A., Johnson, J.M., Awale, R., 2015. Stabilized Nitrogen Fertilizers and Application Rate Influence Nitrogen Losses under Rainfed Spring Wheat. *Agron. J.* 107, 1885-1894.
- Urbaniak, S.D., Caldwell, C.D., Zheljazkov, V.D., Lada, R., Luan, L., 2008. The effect of cultivar and applied nitrogen on the performance of *Camelina sativa* L. in the Maritime Provinces of Canada. *Can. J. Plant Sci.* 88, 111–119.
- Wienhold, B.J., Ardell, D., Halvorson, A.D., 1999. Nitrogen mineralization responses to cropping, tillage, and nitrogen rate in the northern great plains. *Soil Sci. Soc. Am. J.* 63, 192–196.

- Zaman, M., Nguyen, M., Blennerhassett, J., Quin, B., 2008. Reducing NH_3 , N_2O and NO_3^- -N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers. *Biol. Fertil. Soils* 44, 693–705.
- Zubr, J. 1997. Oil-seed crop: *Camelina sativa*. *Ind. Crops Prod.* 6: 113-119. doi:10.1016/S0926-6690(96)00203-8.

Figure captions

Fig1: Monthly precipitation (a) and average air temperature (b) along with their long-term averages in central Montana during the experiment.

Fig.2: Effect of tillage and nitrogen source on camelina grain yield. Error bars represent LSD ($P < 0.05$).

Fig. 3: Dose response of camelina grain yield (a), biomass (b), grain oil content (c), protein content (d), and oil yield (e) to nitrogen fertilizer. Symbols represent data averaged over tillage systems (CT and NT), sources of N fertilizer (urea and SuperU), and years while lines were derived from regression coefficients. Error bars represent LSD ($P < 0.05$).

Table 1: Soil general characteristics (samples were taken before beginning of the experiment)

Soil depth (cm)	Nitrate-N (mg kg ⁻¹)	P-Olsen (mg kg ⁻¹)	K (mg kg ⁻¹)	S (mg kg ⁻¹)
0-15	7.3	16	292	5
15-30	6.0	5	226	4

Table 2. ANOVA table for camelina dependent variables with sources of variation, effect type, and degrees of freedom. The *F* values and significance level for fixed effects and mean squares (MS) for random effects are shown. DF for pooled error are given in parenthesis below each error MS. Random effects are shown in bold type

Source of Variation	Effect	DF	Grain yield	Biomass	HI	Oil content	Oil yield	Protein
Year	RE	1	500569	7694840	0.722	456.99	357	180.19
Block (Year)	RE	6	89362	523669	0.006	4.09	12277	2.95
Till	FE	1	12.28**	15.71**	0.14	0.50	9.89**	1.04
NS	FE	1	17.87**	9.81**	7.83**	0.00	12.68**	0.01
Till*NS	FE	1	4.65*	3.95	0.18	2.84	2.82	2.25
NR	FE	2	14.95**	17.95**	1.17	8.89**	12.69**	33.98**
NR _{Linear}	FE	1	29.60**	32.19**	0.47	15.40**	31.26**	69.87**
NR _{Quadratic}	FE	1	0.21	2.04	2.29	3.16	0.50	0.72
Till * NR	FE	2	1.43	1.27	0.18	0.01	0.57	0.64
Till * NR _L	FE	1	0.11	0.00	0.41	0.01	0.00	0.24
Till * NR _Q	FE	1	3.02	2.48	0.00	0.00	0.53	1.04
NS* NR	FE	2	1.05	0.66	1.31	0.51	1.12	0.04
NS* NR _L	FE	1	1.22	1.51	0.02	0.93	0.36	0.05
NS* NR _Q	FE	1	1.60	0.02	3.08	0.12	1.10	0.00
Till *NS* NR	FE	2	1.20	1.29	2.49	1.13	1.00	0.43
Till *NS* NR _L	FE	1	0.56	1.85	6.26*	0.39	0.95	0.24
Till *NS* NR _Q	FE	1	2.12	0.62	0.11	2.13	1.14	0.55
Pooled error	RE		60002	255399	0.002	1.84	6749	1.76
			(67)	(62)	(58)	(69)	(59)	(69)

* Significant at the 0.05 level.

** Significant at the 0.01 level.

Values in parenthesis below each pooled error mean square are df for that error.

Acronyms

FE, fixed effect; RE, random effect.

Till, tillage system; NS, source of nitrogen (urea vs. SuperU); NR, rate of nitrogen fertilizer.

Table 3: Main effects of tillage and source of nitrogen on camelina dependent variables. Values are least square means provided by LSMEANS statement in PROC MIXED of SAS. When F test rejected null hypothesis, LSD values (P=0.05) were calculated.

Experimental factors		Grain yield (kg ha ⁻¹)	Biomass (kg ha ⁻¹)	HI	Oil content (%)	Oil Yield (kg ha ⁻¹)	Protein (%)
Tillage	CT	920a	2528a	0.38	34.7	314a	27.1
	NT	731b	2097b	0.38	35.0	254b	26.8
	<i>LSD</i>	<i>106</i>	<i>226</i>	<i>ns</i>	<i>ns</i>	<i>37.5</i>	<i>ns</i>
N source	Urea	709b	2137b	0.36b	34.8	248b	27.1
	SuperU	940a	2488a	0.40a	34.9	320a	27.0
	<i>LSD</i>	<i>106</i>	<i>226</i>	<i>0.02</i>	<i>ns</i>	<i>37.5</i>	<i>ns</i>

Means with similar letters are not statistically significant at P<0.05.

Fig1: Monthly precipitation (a) and average air temperature (b) along with their long-term averages in central Montana during the experiment.

Fig.2: Effect of tillage and nitrogen source on camelina grain yield. Error bars represent LSD ($P<0.05$).

Fig. 3: Dose response of camelina grain yield (a), biomass (b), grain oil content (c), protein content (d), and oil yield (e) to nitrogen fertilizer. Symbols represent data averaged over tillage systems (CT and NT), sources of N fertilizer (urea and SuperU), and years while lines were derived from regression coefficients. Error bars represent LSD ($P < 0.05$).