Cropping Systems Affect Wheat Yields, Nitrogen Use Efficiency, and Nitrous Oxide Emission

Yesuf Assen Mohammed and Chengci Chen*

ABSTRACT

Cropping systems include mainly cropping sequence, tillage, and fertilizer management practices. Information on the impact of these practices on yields, nutrient use efficiency, and greenhouse gas emission is limited. An experiment was conducted over a 2-yr period in split-split plot design to determine the effects of these practices on wheat (Triticum aestivum L.) grain and protein yields, agronomic nitrogen use efficiency (ANUE), and nitrous oxide (N₂O) emission. The cropping sequences were chemical fallow–wheat (F-W), dry pea (Pisum sativum L.)–wheat (P-W), and camelina (Camelina sativa L. Crantz)–wheat (C-W). Tillage methods were no-till (NT) and sweep till (ST). Nitrogen fertilizer sources included urea (U) and Super U (SU), each applied at 0, 45, and 90 kg N ha⁻¹. The result showed that the interaction of cropping sequence and tillage methods affected grain yield and ANUE in one of the two growing seasons. Replacing chemical fallow with dry pea or camelina reduced wheat grain yields by at most 15%, but the additional income from dry pea or camelina could offset this yield loss. Application of 45 kg N ha⁻¹ increased grain yield and improved grain protein content compared with 0 kg N ha⁻¹, regardless of N source. The highest protein yields (366 and 475 kg ha⁻¹ in 2013 and 2014, respectively) were recorded at 90 kg N ha⁻¹. The N fertilizer source had no effect on grain and protein yields and ANUE. The ST method and application of SU resulted in a lower flux of N₂O emission than NT and U, respectively.

Core Ideas
• Replacing chemical fallow with dry pea or camelina reduced wheat grain yield.
• Nitrogen fertilizer sources and tillage methods did not affect grain yield.
• The no-till method improved grain protein yield in one of the two seasons.
• Agronomic nitrogen use efficiency improved with no-till than sweep till.
• Sweep till and super urea tend to reduce the flux of N₂O emission.


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SOIL TILLAGE, CONSERVATION, AND MANAGEMENT

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Abbreviations: ANUE, agronomic nitrogen use efficiency; C-W, camelina–wheat; CT, conventional till; DCD, dicamba; F-W, fallow–wheat; GC, gas chromatograph; NBPT, N-(n-butyl) phosphorothioic triamide; N₂O, nitrous oxide; NGP, northern Great Plains; NIR, near-infrared reflectance; NT, no-till; P-W, pea–wheat; ST, sweep till; SU, Super U; U, urea.
Agricultural researchers promote no-till (NT) systems in temperate semiarid regions to capture snow, minimize evaporation loss, reduce soil erosion, and increase energy use efficiency (Grandy et al., 2006; Halvorson et al., 2006; Sainju et al., 2015). Sweep till (ST) is a shallow operation widely practiced in central Montana (personal observation). It is used to uproot weeds, promote water infiltration (by breaking the soil crust), and facilitate seed germination. Contrasting results in terms of grain yield increases have been recorded due to the use of various tillage methods (Halvorson et al., 2006; De Vita et al., 2007). A 12% wheat grain yield increase was reported with NT compared with conventional till (CT) (Halvorson et al., 1999); yet others reported lower wheat grain yield with NT than with CT (Rieger et al., 2008). Pittelkow et al. (2015) reviewed several research reports in the literature to determine the variables that influence whether crops yield better with NT or CT. The authors showed that several factors contribute to the success of NT and suggested that site-specific targeting and system adaptation are necessary to optimize NT performance and contribute to food production goals.

The NT system leaves more crop residue on the surface than CT. This increased residue could induce more urease production, leading to more NH$_3$ volatilization from applied N fertilizer than CT. Rochette et al. (2009) showed that urease activity and NH$_3$ loss were higher in NT than in CT. Other studies also showed that the loss of applied N fertilizer through NH$_3$ volatilization could be substantial from NT compared with CT (Roscoc et al., 2000; Rojas et al., 2012). In addition, N immobilization in the NT system could be greater than CT, especially in cereal-dominated cropping systems, thus creating N deficiency, particularly early in the growing season. Halvorson et al. (2006) found that the response of wheat grain yield to N fertilizer application in a CT system was 16% higher than with NT for the same N application rate. This indicates that the different tillage methods may require different N fertilizer management strategies to avoid N deficiency and yield reduction.

Nitrogen fertilizer is the largest input cost in cereal-dominated cropping systems (Cassman et al., 2002). Nevertheless, agronomic N use efficiency (ANUE) (calculated as kg of grain yield increase kg$^{-1}$ of N fertilizer applied) rarely exceeds 33% (Raun and Johnson, 1999). Attempts have been made to enhance the efficiency of N fertilizer by reducing applied N loss and synchronizing its availability in the soil with plant N demand. Urea is one of the most widely used N fertilizers. It is believed that addition of a urease and nitrification inhibitors in urea could reduce N losses. The use of urease inhibitor in urea has been shown to minimize NH$_3$ loss from applied urea (Engel et al., 2017). However, the agronomic benefits of adding inhibitors in urea have been inconsistent due to edaphic and climatic variations and differences in agronomic management practices (Clay et al., 1990; Wolt, 2004; Randall and Vetsch, 2005; Chen et al., 2008; Parkin and Hatfield, 2010; Mohammed et al., 2015a). Therefore, evaluation of the advantage of using enhanced efficiency N fertilizers under different crop rotations, tillage methods, and N application rates is needed.

Nitrogen fertilization contributes to N$_2$O emission. Nitrous oxide is a greenhouse gas and a gas involved in the depletion of the ozone layer. It is emitted from the soil during nitrification and denitrification processes (Robertson et al., 2013). Research results showed that the use of urease and nitrification inhibitors together with urea decreased N$_2$O emission by 43% compared with applying urea alone (Sanz-Cobena et al., 2012). Nitrous oxide emission from arable land increased by 30-fold as water-filled soil pore space increased from 60 to 80% (Dobbie and Smith, 2001). Grandy et al. (2006) found that average N$_2$O emissions were similar in CT and NT systems. These showed that the success of using inhibitors (with N fertilizers) and tillage methods to reduce N$_2$O emission depends on cropping system, soil, and climatic variables (Grandy et al., 2006; Zaman et al., 2009).

Research on the effects of cropping sequence, tillage method, and N fertilizer source and rate on wheat grain and protein yields, ANUE, and N$_2$O emission is limited in the NGP of the United States. We hypothesized that the use of NT, replacing summer fallow with dry pea or camelina, together with the use of enhanced efficiency N fertilizer, will improve soil moisture content, synchronize applied N availability in the soil with plant N demand, enhance N uptake, and minimize applied N fertilizer losses. These eventually will increase wheat grain and protein yields, improve ANUE, and reduce N$_2$O emission. The objective of this study was to determine the effect of cropping sequence, tillage method, and N fertilizer management practices (N source and rate) on wheat grain and protein yields, ANUE, and N$_2$O emission.

**MATERIALS AND METHODS**

**Site Description**

The experiment was conducted in 2013 and 2014 at the Central Agricultural Research Center of Montana State University, located at 47°03' N, 109°57' W and 1400 m above sea level near Moccasin, MT. The long-term mean annual precipitation is 388 mm with mean air temperature of 6°C. The growing season (September–August) precipitation and temperature during the experiment and long-term means (1909–2014) are shown in Table 1. The soil is shallow (usually less than 0.6 m depth) and is classified as a Judith clay loam (fine-loamy, carbonatic, frigid Typic Calciustolls). Soil samples collected from the top soil (0–0.15 m) were dried, ground, and sieved to pass through a 2-mm sieve. The soil samples were tested following standard procedures as described by Mohammed et al. (2015a). The soil contained 38 g kg$^{-1}$ soil organic matter, 1.54 g kg$^{-1}$ total N, 13 mg kg$^{-1}$ NO$_3$–N, and 7 mg kg$^{-1}$ available P with pH of 7.2.

**Experimental Design and Treatment Structure**

The experiment was set up in a split-split plot design with four replications. The main-plot treatments were cropping sequences, sub-plot treatments were tillage methods, and the sub-sub plot treatments were factorial combinations of N fertilizer sources and N rates. The plot size for main, sub, and sub-sub plots were...
Table I. Crop year monthly (September–August) total precipitation (mm), mean maximum and minimum air temperature (°C) for 2013 to 2014, and long-term means (1909–2014) at Moccasin, MT.

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation, mm</th>
<th>Maximum Temperature</th>
<th>Minimum Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept.</td>
<td>2</td>
<td>97</td>
<td>35</td>
</tr>
<tr>
<td>Oct.</td>
<td>32</td>
<td>40</td>
<td>23</td>
</tr>
<tr>
<td>Nov.</td>
<td>14</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Dec.</td>
<td>4</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Jan.</td>
<td>6</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Feb.</td>
<td>7</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Mar.</td>
<td>3</td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td>Apr.</td>
<td>17</td>
<td>16</td>
<td>31</td>
</tr>
<tr>
<td>May</td>
<td>81</td>
<td>42</td>
<td>66</td>
</tr>
<tr>
<td>June</td>
<td>96</td>
<td>62</td>
<td>79</td>
</tr>
<tr>
<td>July</td>
<td>43</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>Aug.</td>
<td>25</td>
<td>171</td>
<td>41</td>
</tr>
</tbody>
</table>

54.8 × 7.6 m, 27.4 × 7.6 m, and 9.1 × 3.8 m, respectively. The row spacing was 0.3 m for both wheat, dry pea, and camelina.

The cropping sequences were chemical fallow–wheat (F-W), dry pea–wheat (P-W), and camelina–wheat (C-W). The dry pea and camelina were seeded in 2012 and 2013 following the design to evaluate their effects in 2013 and 2014, respectively. Both phases of the rotations were present each year to avoid confounding effects. Tillage treatments were NT and ST. The NT treatment involved direct sowing of the seeds into stubble. Sweep tillage consisted of two passes of a sweep cultivator in an angle, the undercut sweep knife is about 0.15 m wide, and spacing was 0.3 m for both wheat, dry pea, and camelina.

Nitrogen sources were urea (U) and Super U (SU) (Koch Agronomic Services LLC, Wichita, KS), each applied at 0, 45, and 90 kg N ha–1. Super U contains N-(n-butyl) phosphorothioic triamide (NBPT) (urease inhibitor) and dicyandiamide (DCD) (nitrification inhibitor). The NBPT and DCD were applied at 9 and 0.41 m, respectively, with inside volume of 17,100 mL. After all the residues left on the surface after harvest each year.

The objective of this experiment, superimposed on the experiment described previously, was to determine the effect of N fertilization (source and rate) and tillage method on the N2O emission

\[ \text{ANUE} = \frac{(Y_F - Y_C)}{\text{ANrate}} \]

where YFp and YCp are grain yields (kg ha–1) from fertilized and control plots (no N fertilization), respectively, and ANRate refers to applied N fertilizer rate (kg N ha–1).

Nitrogen Oxide Emission

Experiment Setup and Measurement

Glyphosate ([N-(phosphonomethyl) glycine]) was sprayed at the rate of 0.53 kg a.i. ha–1 with 150 L H2O ha–1 as a pre-plant weed control in both NT and ST plots. Each year, between the last week of May and first week of June depending on broadleaf weed growth stage, 2,4-D amine 4 (dimethyamine salt of 2,4-dichlorophenoxyacetic acid) was sprayed at 0.67 kg a.i. ha–1 with 150 L H2O ha–1 only on the wheat plots. In mid-May, Assure II {Quizalofop P-ethyl ethyl-2-\[4-(6-chloroquinoxalin-2-yloxy)-phenoxy\] propionate} (DuPont, Wilmington, DE) was sprayed at 0.16 kg a.i. ha–1 with 150 L H2O ha–1 to control grass weeds only in the dry pea and camelina plots.

Wheat was harvested with a plot combine harvester (Wintersteiger, Salt Lake City, UT) on 12 Aug. 2013 and 19 Aug. 2014. Grain moisture content was measured using a grain moisture analyzer (Agrimat, Owensboro, KY) and grain yield adjusted to 125 g kg–1 moisture content before statistical analysis. Grain protein concentration was measured using a near-infrared reflectance (NIR) analyzer calibrated for wheat (Perten Instruments, Hägersten, Sweden) (McVay and Khan, 2011). Grain protein yield was calculated by multiplying grain yield and grain protein concentration. Agronomic N use efficiency was calculated using the following equation:

\[ \text{ANUE} = \frac{(Y_F - Y_C)}{\text{ANrate}} \]

The plan for this experiment was to use winter wheat as a test crop, but the seed bed in fall 2012 was too dry for seeding. Therefore, spring wheat (cv. Chateau) was seeded in spring 2013. In 2014 cropping season, winter wheat (cv. Yellowstone) was seeded. The cultivars were Montech 4152 and Blaine Creek for dry pea and camelina, respectively. Seeding rates for wheat, dry pea, and camelina were 65, 180, and 5.6 kg ha–1, respectively. The seeding rates were adjusted based on germination percentage, seed weight, and recommended number of live seeds m–2.

Winter wheat was planted the second week of September while spring wheat, dry pea, and camelina were seeded between the last week of March and the first week of April each year. The ConservaPak air seed drill (ConservaPak, Indian Head, SK, Canada) was used for seeding. Both winter wheat and dry pea were seeded at 5 cm deep but camelina was seeded 1 to 2 cm deep.

Wheat was harvested with a plot combine harvester (Wintersteiger, Salt Lake City, UT) on 12 Aug. 2013 and 19 Aug. 2014. Grain moisture content was measured using a grain moisture analyzer (Agrimat, Owensboro, KY) and grain yield adjusted to 125 g kg–1 moisture content before statistical analysis. Grain protein concentration was measured using a near-infrared reflectance (NIR) analyzer calibrated for wheat (Perten Instruments, Hägersten, Sweden) (McVay and Khan, 2011). Grain protein yield was calculated by multiplying grain yield and grain protein concentration. Agronomic N use efficiency was calculated using the following equation:

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where YFp and YCp are grain yields (kg ha–1) from fertilized and control plots (no N fertilization), respectively, and ANRate refers to applied N fertilizer rate (kg N ha–1).
seeding wheat and camelina, the frame of the chamber was inserted into the soil between crop rows to a depth of 0.05 m. The frame and the chamber were separate pieces with the chamber being deployed during sampling, then removed to allow the frame to be left open until the next sampling day. Urea and SU were broadcasted inside the chamber by hand on 21 May 2013 (common N top dressing time). Before taking gas samples, air in the vials was evacuated using a vacuum pump (Gardner Denver, Inc., Welch Vacuum Technology, Niles, IL). Twenty-mL air samples were collected from the chamber headspace at 0, 0.25, and 0.5 h after chamber deployment through a rubber septum and injected into evacuated vials using a medical syringe. Air samples were collected 2 d wk–1 for 3 mo starting from 22 May 2013. The gas samples were collected between 1100 and 1200 h Mountain Standard Time. Standard and blank gas samples were taken in the field each day of gas sampling. The N₂O was analyzed using gas chromatograph (GC) (Model 3800) (Varian, Inc., Walnut Creek, CA). The GC was configured with a 1-mL sample loop, a 0.5-m long (3.2-mm i.d.) Haysep N (80/100) backflush column (VICI Valco Instruments Corp. Houston, TX), and a 2-m (3.2-mm i.d.) Haysep D (80/100) analytical column. About 2.5 mL of gas from the vial was automatically injected into the GC. The carrier gas was a mixture of Ar and CH₄ (95:5) with flow rate of 60 mL min–¹. The injector, column oven, and electron capture detector temperatures were 40, 120, and 360°C, respectively. The sample retention time was 3 min.

**Statistical Analysis**

Homogeneity of variance and normality of data distribution assumptions were validated using Proc Univariate of SAS (SAS Institute, 2011) and a Levene’s test (Levene, 1960), respectively. The N₂O data were log-transformed. The PROC GLM procedure in SAS (version 9.3) was used for data analysis (SAS Institute, 2011). The degree of freedom and thus the denominator used to calculate the different F ratios varied for the different factors and interactions based on split-split plot design. Spring wheat and winter wheat were planted in 2013 and 2014, respectively. Therefore, ANOVA was run for each year due to differences in mean grain yield between the 2 yr, probably due the variation in precipitation between years and the differences in yield potential of the two wheat classes. Differences in inter-seasonal precipitation in the area are common and have been shown in our previous publications (Mohammed et al., 2014, 2016). In addition, it is recommended to analyze and report individual years data independently (Raun et al., 2017). When ANOVA showed significant treatment effect (P ≤ 0.05), the Tukey HSD test at P = 0.05 was to differentiate treatment mean effects.

**RESULTS AND DISCUSSION**

**Weather**

The total crop year precipitation in 2013 and 2014 were 15% lower and 41% higher, respectively, than the long-term mean of 388 mm (Table 1). These inter-seasonal differences in precipitation resulted in low soil moisture in fall of 2012, promoting the decision to seed a spring wheat cultivar in the spring of 2013 instead of a fall-seeded winter wheat cultivar as originally planned. Generally, the mean maximum and minimum air temperatures during the crop growing period were similar to the long-term means for both years except that minimum air temperatures from February to June of 2014 were lower than long-term means.

Results presented and discussed are from a 2-yr dataset (2013 and 2014) for wheat grain yield, grain protein yield, and ANUE and a1-yr dataset (2013) for N₂O emission. The N₂O dataset is limited to one growing season but it will give background information comparing the effects of tillage method, N source and rate and, most importantly, the effects of growing wheat and camelina on N₂O emission.

**Wheat Grain Yield**

In 2013, the interaction of cropping sequence and tillage treatments was significant (Table 2). These interaction means show that the highest mean grain yield (2321 kg ha⁻¹) was recorded following fallow and under ST. Soil surface crusting is a common problem in the surrounding area (observation) and farmers practice shallow tillage such as ST to break the soil crust to enhance infiltration and seed germination. Accordingly, the ST following fallow could have loosened the soil surface to facilitate infiltration, promote seed germination, and eventually increased yield. Blanco-Canqui (2011) showed that NT can induce significant soil water repellency, thus reducing soil moisture recharge compared with CT. In addition, in the temperate semiarid areas, low soil temperature early in the spring is one of the limiting factors delaying greening. Halvorson et al. (2006) showed more plant population in CT than NT plots early in the spring and associated this increase mainly due to increased soil temperature in CT compared with NT. Similarly, the ST system in our study incorporated the residue and exposed the soil. This could have increased soil temperature early in the spring compared with NT, and thus may have contributed to earlier greening, more seedling vigor, and thus explaining the greater yield obtained with CT than with NT.

The cropping sequence treatments resulted in significant wheat grain yield differences in both years (Table 2 and Fig. 1). In 2013, wheat grain yields after fallow (F-W) were 14 and 15% higher than after camelina (C-W) and dry pea (P-W), respectively (Fig. 1a). Similarly in 2014, wheat grain yield after fallow was 15 and 6% higher than after camelina and dry pea, respectively. These results show that replacing summer fallow with either camelina or dry pea could reduce wheat grain yield by as much as 15%. This result is in agreement with previous findings (Lin and Chen, 2014). The greater yield after fallow could be due to improved stored soil moisture, which nearly always limits yields in central Montana due to shallow soil depth and low precipitation. The experimental site has very shallow soil (usually less than 0.6 m), thus affecting soil water storage. However, this yield loss due to fallow replacement could be offset by pea or camelina yields. In addition, replacing summer fallow with these crops diversifies and intensifies the F-W cropping system, adding additional agronomic benefits and ecosystem services (Randall et al., 1997; Miller et al., 2015).

The effect of tillage on wheat grain yield was not significant (Table 2 and Fig. 1b). We expected better grain yield from NT than from ST, mainly due to snow capture and thus improved soil moisture storage. Similar study showed that yields from NT were consistently lower than CT (Pittelkow et al., 2015). Other studies also showed lower grain yield from NT than CT.
systems, probably due to increased soil temperature from the CT systems early in the growing season (Halvorson et al., 2006; Rieger et al., 2008). Even if yield differences between NT and ST is not significant in our study, the NT may contribute to lower input costs by reducing the energy and time needed for cultivating the land, thus making it more preferable than the ST method. In addition, some studies showed that NT improved soil C and N storage and soil aggregation compared with CT (Grandy et al., 2006; Sainju et al., 2015). These indicate that NT could improve overall system productivity in the long run, and this requires long-term evaluation of the experiment.

When averaged over cropping sequences, tillage methods, and N sources, application of 45 kg N ha⁻¹ increased grain yield by 37% compared with the unfertilized treatment in 2013 (Table 2, Fig. 1c). Similarly in 2014, this same application rate resulted in 18% more grain yield than the unfertilized treatment. But the difference in grain yield as application rate

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grain yield</td>
<td>Grain protein yield</td>
</tr>
<tr>
<td>Cropping sequence (Cs)</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Tillage (T)</td>
<td>0.4715</td>
<td>0.1711</td>
</tr>
<tr>
<td>N source (Ns)</td>
<td>0.5309</td>
<td>0.4921</td>
</tr>
<tr>
<td>N rate (Nt)</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Cs × T</td>
<td>0.0122</td>
<td>0.0566</td>
</tr>
<tr>
<td>Cs × Ns</td>
<td>0.2849</td>
<td>0.1933</td>
</tr>
<tr>
<td>Cs × Nr</td>
<td>0.3858</td>
<td>0.0226</td>
</tr>
<tr>
<td>T × Ns</td>
<td>0.8264</td>
<td>0.7483</td>
</tr>
<tr>
<td>T × Nr</td>
<td>0.9401</td>
<td>0.9901</td>
</tr>
<tr>
<td>Ns × Nr</td>
<td>0.8984</td>
<td>0.9660</td>
</tr>
<tr>
<td>Cs × T × Ns</td>
<td>0.7408</td>
<td>0.9103</td>
</tr>
<tr>
<td>Cs × T × Nr</td>
<td>0.1197</td>
<td>0.2318</td>
</tr>
<tr>
<td>Cs × Ns × Nr</td>
<td>0.9283</td>
<td>0.9611</td>
</tr>
<tr>
<td>T × Ns × Nr</td>
<td>0.8373</td>
<td>0.8114</td>
</tr>
<tr>
<td>Cs × T × Ns × Nr</td>
<td>0.9601</td>
<td>0.9758</td>
</tr>
<tr>
<td>Mean</td>
<td>1980</td>
<td>258</td>
</tr>
</tbody>
</table>

Fig. 1. Effects of (a) cropping sequence, (b) tillage method, (c) N rate, and (d) N source on mean grain yield of wheat (kg ha⁻¹) in 2013 and 2014 at Moccasin, MT. Error bars are standard error of the means (n = 48 for each cropping sequence and N rate; and n = 72 for each tillage method and N source). Cam = camelina; Fal = chemical fallow; Pea = dry pea; NT = no-till; ST = sweep till; SU = Super U; U = urea.
increased from 45 to 90 kg N ha\(^{-1}\) was not significant in either growing season (Fig. 1c).

The effect of N fertilizer source was not significant in either year (Table 2). The advantage of using enhanced efficiency N fertilizers depends on the amount and distribution of autumn and spring precipitation (McKenzie et al., 2010; Sistani et al., 2011; Mohammed et al., 2014, 2015a; Thapa et al., 2015). Kyveryga and Blackmer (2014) concluded that N fertilizer with inhibitors may produce a profitable yield response when cumulative spring and summer rainfall is 40% greater than the long-term average. In our previous studies, we also showed that variability in inter-seasonal precipitation amounts caused substantial differences in biomass yield response to N fertilizer application rates and sources (Mohammed et al., 2014, 2015b).

**Grain Protein Yield**

The interaction of cropping sequence and N application rate on protein yield was significant in both growing seasons. In 2013, the greatest mean grain protein yield (366 kg ha\(^{-1}\)) was achieved when spring wheat was seeded on chemical fallow plot with the application of 90 kg N ha\(^{-1}\) compared with other treatments. This same treatment resulted in the greatest protein yield (475 kg ha\(^{-1}\)) in 2014. These increased grain protein yields due to chemical fallow are highly associated with the greater grain yield recorded after fallow than after dry pea or camelina. This could be due to differences in soil moisture storage among the different cropping sequences as discussed above. Similarly, in both growing seasons, W-F produced significantly higher protein yield than the other cropping sequences (Fig. 2a). The protein yield was in the order of F-W > C-W > P-W in 2013 and F-W > P-W > C-W in 2014.

The interaction of tillage and N application rate was significant only in 2014 with the greatest grain protein yield achieved from ST with 90 kg N ha\(^{-1}\) application compared with other treatments. The wheat grain protein yield was significantly greater for ST than NT method (Fig. 2b). This improved grain protein yield from ST is highly associated with the grain yield as explained above.

Grain protein yield increased linearly with increased N application rate when averaged across N sources in both growing seasons (Fig. 2c). The relationship between grain protein yield and N application rate agrees with previous findings (Mohammed et al., 2013). The effect of N fertilizer sources did not show a significant grain protein yield advantage (Fig. 2d). However, there was a tendency for higher grain protein yield from SU compared with U in the wet 2014 growing season indicating that benefits of using enhanced efficiency N fertilizer are associated with above average precipitation, confirming our previous research results (Mohammed et al., 2015a).

**Agronomic Nitrogen Use Efficiency**

The interaction of cropping sequence and tillage method significantly affected ANUE in 2013 (Table 2 and Fig. 3a). The result showed that ST after fallow, and NT after dry pea resulted in the highest ANUE. The lowest ANUE occurred with NT after fallow, and also with ST after dry pea. Cropping sequence had no significant effect on ANUE. Agronomic N use efficiency is an important indicator measuring the benefits of applying N fertilizer in terms of yield increase and environmental consequences. A higher ANUE could mean increased N uptake, improved grain quality, and better economic benefit of using N fertilizer with reduced N loss, thus protecting the environment from pollution.
In 2014, NT resulted in significantly higher (12 vs. 9 kg grain kg N⁻¹ applied) ANUE than ST (Fig. 3b). This higher ANUE from NT could reduce the impact of N fertilizer on water and air pollution compared with ST. This result is in agreement with previous findings (Randall et al., 1997) and shows that NT enhanced nutritional quality (grain protein yield) and improved ANUE at the same time. These increased ANUE could eventually help to reduce undesirable environmental consequences of using N fertilizer. The lower ANUE from ST could be due to loss of applied N fertilizer via leaching since this tillage method could facilitate infiltration that could leach N beyond the root zone.

Increased N fertilizer application rates resulted in reduced ANUE in both growing season regardless of N fertilizer source (Fig. 3c). Results from a similar study indicated that ANUE decreased with increased N rates (Mohammed et al., 2013). The mean ANUE from this study ranged from 7.7 to 15.2 kg wheat grain kg⁻¹ N fertilizer applied. Cassman et al. (2002) showed even wider ranges of ANUE due to differences in weather. It was anticipated that the 2014 winter wheat crop with its longer growing period would respond more to applied N fertilizer than spring wheat seeded in 2013 leading to a higher ANUE, but our results did not support this expectation. This could be with the result of higher precipitation amounts received in 2014 that may have increased N supply from the soil by stimulating microbial activity (organic matter mineralization), thus lowering response to applied N. The ANUE trended to be higher with SU than with U when the soil was relatively wet in 2014 but the difference was not significant (Fig. 3d).

**Nitrous Oxide Emission**

Nitrous oxide emission was undetectable on some days during the period from N fertilizer application to harvesting time. Therefore, we present results only from days following N fertilization that showed detectable N₂O flux. As depicted in Fig. 4a, N₂O flux was greater on 28 May for all treatments. The site received a total of 20 mm of rainfall between 24 and 28 May. This was the highest 5-d rainfall that occurred during the growing season for this site. This high rainfall amount may have increased soil microbial activity and chemical reactions in the soil resulting in more production and emission of N₂O on 28 May than any other day.

The effect of tillage on N₂O flux was significant on 24 May (Table 3) when averaged over N fertilizer sources and rates. Nitrous oxide emission was 112% greater with NT than with ST on this date (Fig. 4a). It is worth mentioning that NT unexpectedly showed a tendency to produce a higher mean N₂O flux than ST over the entire experimental period. This increased emission could be due to there being more stubble on the soil surface with NT than ST. Stubble can triguer more urease activity, thus more urea hydrolysis leading to more nitrification and denitrification. These processes eventually could result in more N₂O production and emission. This result is in agreement with Pittelkow et al. (2015), whose findings showed increased N₂O emission from NT compared with CT. Other researchers indicated that the 62 and 44% for NT and CT, respectively (Linn and Doran, 1984). This difference in percentage of water-filled pore space could explain the more N₂O emission from NT than CT.

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temporary nitrification inhibition. Other researchers have reported that N₂O emission was reduced when urease and nitrification inhibitors were used with urea alone (Halvorson et al., 2008; Zaman et al., 2009).

On 24 May and 5 June, N₂O flux was higher from spring wheat plots than camelina (Fig. 4d). This might be explained by our observation that canopy coverage was greater with spring wheat than with camelina. A more dense canopy likely minimized moisture loss via evaporation resulting in greater soil moisture content in the spring wheat plots compared with camelina plots. The resulting increase in soil moisture could have triggered more microbial activity and thus more N₂O production and emission from spring wheat plots compared with camelina plots. Some studies showed that increased soil moisture increased N₂O emission due to enhanced nitrification and denitrification (Maag and Vinther, 1996; Ruser et al., 2006).

These results indicate that N fertilization of camelina in the existing cropping systems produced less N₂O emission compared with spring wheat. However, long-term research with more data is needed to elucidate why N₂O emission was lower from camelina plots than from spring wheat plots. Perhaps camelina root exudates have some inhibitory effect on microbial activity, thereby limiting the nitrification and denitrification processes that are responsible for N₂O production. This result is from one growing season data set. Monitoring of N₂O emission over a longer time period would help make a more reliable conclusion; however, these results from a single season and short sampling time (the limitation of the study) could give background information for future research in the area.

**SUMMARY**

The interaction of cropping sequence and tillage method significantly affected wheat grain yield with greatest grain yield being achieved after fallow with ST method. Generally, wheat grain yield after chemical fallow was greater than following dry pea or camelina. However, the yield from dry pea or camelina could offset this yield penalty. Application of 45 kg N ha⁻¹ resulted in a significant grain yield increase when averaged over N fertilizer sources compared with no N fertilization. The grain yield difference between the 45 and 90 kg N ha⁻¹ application rates was not significant. There was no yield difference between the two N fertilizer sources (U and SU). No-till enhanced ANUE compared with ST in the year with above-normal precipitation, but the difference between these two tillage methods was not pronounced when conditions were drier than average. As expected, ANUE decreased as N application rate increased and tended to be higher for SU than U in wet conditions.
Application of N fertilizer increased N$_2$O flux; however, the emission rate was lower with SU than with U, showing the environmental benefit of using an enhanced efficiency N fertilizer. Nitrous oxide flux was lower for ST than for NT. A more long-term evaluation of these practices is needed to collect more agronomic and economic data including the impacts on soil organic matter, N management, seedling vigor, soil moisture, soil temperature, and the relative values of costs and benefits.

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