Fall Rye Reduced Residual Soil Nitrate and Dryland Spring Wheat Grain Yield

Ben W. Thomas, Francis J. Larney, Martin H. Chantigny, Claudia Goyer, and Xiying Hao*

ABSTRACT
Limited information about how cover crop management impacts the agronomic performance of succeeding annual crops in semiarid regions constrains cover crop utilization. Therefore, over 2 yr we quantified how cover crop species (fall rye [Secale cereale L., ‘AC Remington’] or oilseed radish [Raphanus sativus L., ‘Tillage radish’]) and nutrient source (compost or inorganic fertilizer) affected cover crop biomass and N uptake, soil nitrate N (NO₃−-N) and ammonium N (NH₄−-N), and the agronomic performance of the succeeding spring wheat (Triticum aestivum L.) test crop. Fall rye reduced pre-plant NO₃−-N by 2 to 18 times compared with oilseed radish, and reduced spring wheat grain yields by 38 to 58% compared with amended soils with no cover crop and oilseed radish. Inorganically fertilized soils led to 21% greater pre-plant soil NO₃−-N concentrations than the compost-amended soil in 2013–2014 but nutrient source did not significantly affect NO₃−-N concentrations in 2014–2015. A quadratic function explained 93% of the variability between pre-plant soil NH₄−-N plus NO₃−-N (0–7.5-cm depth) and spring wheat grain yield in 2014, indicating that the N supply limited spring wheat grain yield. We conclude that fall rye scavenged residual NO₃−-N better than oilseed radish during the non-growing season, particularly during the spring period when this perennial species assimilates N, but under semiarid conditions it may decompose and mineralize too slowly to supply N at the right time for the subsequent crop, while oilseed radish tended to boost spring wheat grain yield.

Core Ideas
- Fall rye reduced pre-plant nitrate by 2 to 18 times compared with tillage radish.
- Fall rye reduced dryland spring wheat grain yield by 38 to 58% compared with tillage radish.
- Pre-plant soil NH₄−-N plus NO₃−-N explained 93% of spring wheat grain yield variability.

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POST-HARVEST SEEDING of cover crops reduces the risk of wind erosion and nutrient loss through leaching and runoff during the non-growing season, while increasing the biodiversity and resilience of prairie cropping systems (Martens et al., 2015). Yet, few studies have directly investigated late-summer to-fall seeded cover crop management practices in semiarid regions (e.g., Moyer and Blackshaw, 2009; Blackshaw et al., 2010; Liebig et al., 2015; Thomas et al., 2016a), which constrains their adoption by farmers (Liebig et al., 2015). A better understanding of how cover crop management practices impact subsequent annual crop performance could provide important knowledge to advance the use of cover crops in semiarid regions of North America.

Thorup-Kristensen (1993) coined the term “pre-emptive competition” to describe the effect whereby cover crops assimilate N, but then decompose and mineralize too slowly to supply the retained N to the succeeding crop. Thus, the N supply to the subsequent crop depends on complex interactions among the cover crop characteristics, soil and climatic properties, and the succeeding crop itself (Thorup-Kristensen et al., 2003). For instance, oilseed radish decomposed more quickly than barley (Hordeum vulgare L.) in southern Manitoba (Halde and Enz, 2016), while glyphosate [N-(phosphonomethyl)glycine]-killed fall rye consistently reduced unfertilized spring wheat yield relative to no cover crop in southern Alberta (Moyer and Blackshaw, 2009). Whether oilseed radish may scavenge N as efficiently as fall rye and subsequently decompose and mineralize to supply N to the succeeding crop has not been determined in southern Alberta.

Fall rye and oilseed radish are two contrasting cover crops. Fall rye is a perennial monocotyledon with an extensive fibrous root system, while oilseed radish is an annual dicotyledon with a large taproot. Fall rye must be killed prior to planting the succeeding cash crop, chemical burndown (herbicide treatment) in spring being a common method, whereas oilseed...
radish winter kills. While radish cover crops may be as effective as cereal rye in assimilating available N in topsoil, and more effective capturing available N from deep soil layers (Dean and Weil, 2009; Lacey and Armstrong, 2015), whether that N will become available for the subsequent crop is uncertain in semiarid regions where a lack of moisture may limit biotic decomposition and mineralization of plant residues (Helgason et al., 2014). Furthermore, little is known about whether compost or inorganic fertilizer may better aid cover crop establishment while reducing the risk of NO$_3^-$–N loss.

Utilizing composted beef cattle manure as a nutrient source in semiarid environments is inconsistent in dryland production systems for two primary reasons: (i) the plant-available N is typically ≤12% of the total N in the composted manure (Helgason et al., 2007; Li et al., 2016; Thomas et al., 2016b) and (ii) rainfall and thus soil moisture restricts decomposition and mineralization rates in semiarid climates (Helgason et al., 2014), which limits the contribution of organic N from organic amendments to the plant-available N pool in dryland cropping systems (Hao et al., 2016). In particular, during dry and normal precipitation growing seasons the N supply for crops is limited by soil moisture, while in above-average precipitation growing seasons the decomposition and mineralization of organic N occurs with less or no moisture limitation relative to crop N demand (Hao et al., 2016). Perennial crops such as fall rye may be better suited to capture nutrients from compost-amended soils, while annual crops like oilseed radish may prefer the plant-available N supplied by inorganic fertilizer, because perennial crops utilize resources more efficiently than annual crops (Jordan et al., 2007).

Long-term crop rotation studies have investigated the inclusion of a fall rye cover crop in crop rotations assessing soil conservation management practices in southern Alberta, but a direct cover crop effect could not be determined due to the longer term rotational nature of the study (Larney et al., 2016). Thus, the objective of this study was to directly quantify how cover crop species (fall rye or oilseed radish) and nutrient source (compost or inorganic fertilizer) affects cover crop dry biomass, C accumulation and N uptake, soil NO$_3^-$–N and NH$_4^+$–N dynamics, and the agronomic performance of unfermented beef cattle feedlot manure (FRC), fall rye with inorganic fertilizer (FRF), oilseed radish cultivar Tillage radish with composted beef cattle feedlot manure (ORC), oilseed radish with inorganic fertilizer (ORF), no cover crop with composted beef cattle feedlot manure (NCC), no cover crop with inorganic fertilizer (NCF), and a non-amended soil with no cover crop as a control (CON).

The composted beef cattle feedlot manure (hereafter–compost) and inorganic fertilizer were broadcasted on all plots, except CON, on 27 and 28 Aug. 2013 and 15 Aug. 2014 (Table 1). Each year, the inorganic fertilizers [ammonium nitrate (45 kg N ha$^{-1}$) and triple superphosphate (10 kg P ha$^{-1}$)] were broadcasted with a Valmar 1255 TR Pull Type Pneumatic Granular Applicator, while the compost was broadcasted by hand with shovels at a rate of 100 kg total N ha$^{-1}$. The plots were then disked to incorporate the fertilizer and compost to ~10-cm depth. Regardless of the compost and inorganic N fertilizer application rates, it is nearly impossible to apply the same plant-available N given the large organic-N fraction (~90%) in the compost. Here we assumed that the compost would supply the equivalent of an inorganic N rate of about 45 kg N ha$^{-1}$ over each 1-yr period. Given about a 25% recovery of compost total N in compost-amended soils and a 55% recovery of inorganic N fertilizer these rates were calculated to provide about 25 kg N ha$^{-1}$ as a cover crop starter N source. Each year, compost chemical composition analyses were conducted on a dry matter basis to capture differences in compost chemical composition. In 2013–2014, the compost (683 g dry matter kg$^{-1}$) contained 171 g total C kg$^{-1}$ and 15.4 g total N kg$^{-1}$ as determined by dry combustion (NA 1500 Series 2, Carlo Erba Instruments, Milan, Italy), and 30.2 mg NH$_4^+$–N kg$^{-1}$ and 1140 mg NO$_3^-$–N kg$^{-1}$ as determined by 2 mol L$^{-1}$ KCl extraction. The NH$_4^+$–N and NO$_3^-$–N concentrations were determined with an automated colorimeter (Astoria-Pacific 305D Detector, Astoria-Pacific Inc., Clackamas, OR). In 2014–2015, the compost (672 g dry matter kg$^{-1}$) contained 173 g total C kg$^{-1}$, 16.0 g total N kg$^{-1}$, 20.1 mg NH$_4^+$–N kg$^{-1}$ and 607 mg NO$_3^-$–N kg$^{-1}$, which were determined as described above.

### Materials and Methods

#### Study Site and Treatments

A 2-yr field study was conducted at the Agriculture and Agri-Food Canada Lethbridge Research and Development Centre in Lethbridge, AB (49°38’N, 112°48’W; altitude: 929 m), with mean annual air temperature of 5.9°C and mean annual precipitation of 380 mm (1981–2010). The soil is calcareous with clay loam texture and is classified as an Orthic Dark Brown Chernozem (Soil Classification Working Group, 1998). Two adjacent field sites were selected and cropped to conventionally managed spring wheat cultivar AC Lillian under rainfed conditions. The study began after the spring wheat harvest in August 2013 and was repeated on an adjacent field site in August 2014. Each field site was divided into four 37.2 by 10 m complete blocks with 10-m buffers between blocks. There was a 2-m buffer between plots within each block and a 10-m headland buffer around the field sites. Seven experimental treatments were randomly assigned to 3.6 by 10 m plots within each block for a total of 28 experimental units. The treatments were fall rye cultivar AC Remington with composted beef cattle feedlot manure (FRF), fall rye with inorganic fertilizer (FRF), oilseed radish cultivar Tillage radish with composted beef cattle feedlot manure (ORC), oilseed radish with inorganic fertilizer (ORF), no cover crop with composted beef cattle feedlot manure (NCC), no cover crop with inorganic fertilizer (NCF), and a non-amended soil with no cover crop as a control (CON).

| Table 1. Experimental timeline from 2013 to 2015. |
|---|---|---|---|---|---|---|---|
| Trial | Fertilized | Planted cover crops | Sampled cover crop biomass | Sampled fall rye | Killed fall rye | Pre-plant soil sampling | Planted spring wheat | Harvested spring wheat |

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The cover crops were seeded on 30 Aug. 2013 and 15 Aug. 2014 at 7.8 kg seed ha$^{-1}$ for oilseed radish and 90 kg seed ha$^{-1}$ for fall rye using a custom double-disk forage seeder at 18-cm row spacing. The cover crop seeding dates differed to enable a longer cover crop establishment period in 2014 than 2013. In 2013, oilseed radish seed was not treated with insecticide and flea beetle [Phyllotreta cruciferae (Goeze)] severely damaged the seedlings, which necessitated re-planting with a liquid seed treatment of Helix [Thiamethoxam] (Syngenta Group Company, Basel, Switzerland) on 16 Sept. 2013 as described above. Each year after seeding, the plots were irrigated until 16 Sept. 2013 and 23 Sept. 2014 to aid cover crop establishment. In 2013, 78 mm of irrigation water was applied, while in 2014, 38 mm of irrigation water was applied. This means that the oilseed radish received minimal irrigation water for establishment in 2013. To kill the fall rye, fall rye plots were treated with a mixture of Roundup Transorb [N-(phosphonomethyl) glycine] [Monsanto Company, St. Louis, MO] at 220 a.e. ha$^{-1}$ plus Heat at 4.2 g ha$^{-1}$ [N was not considered a failure in 2013–2014, but the poor tillage re-planting, it did establish and for that reason the treatment could be more directly evidenced. While tillage radish required fertilized so that the effect of cover crop and nutrient source technical staff availability. The spring wheat plots were not planting dates reflected weather and field conditions along with Deere hoe drill on 4 June 2014 and 5 May 2015. The different plantings reflected weather and field conditions along with technical staff availability. The spring wheat plots were not fertilized so that the effect of cover crop and nutrient source could be more directly evidenced. While tillage radish required re-planting, it did establish and for that reason the treatment was not considered a failure in 2013–2014, but the poor tillage radish establishment should be recognized as a confounding effect that year.

Soil and Plant Sampling and Analysis

Prior to beginning the experiment, soil samples were collected from each plot to determine the background total C, total N, NO$_3$–N, NH$_4$–N, and pH at 0 to 7.5, 7.5 to 15, 15 to 30, and 30 to 60-cm soil layers (Table 2). During the non-growing season, soil samples were collected from the 0 to 15-cm soil layer monthly from October to May (except April each year). Each May, prior to seeding spring wheat, soil was collected from the 0 to 7.5-, 7.5 to 15-, 15 to 30- and 30 to 60-cm layers (14 May 2014 and 5 May 2015). The soil samples were then analyzed for pre-plant NO$_3$–N and NH$_4$–N concentrations by 2 mol L$^{-1}$ KCl extraction (Keeney and Nelson, 2018). The 2 mol L$^{-1}$ KCl-extractable NO$_3$–N and NH$_4$–N concentrations were determined by automated colorimetry as described above for compost analyses.

Cover crop biomass was determined by collecting the aboveground fall rye biomass (27 Nov. 2013 and 6 Nov. 2014), and aboveground oilseed radish biomass (27 Nov. 2013) and the aboveground oilseed radish biomass plus taproots (6 Nov. 2014) from four 0.5 by 0.5 m quadrats per plot. Fall rye biomass was also measured on 12 May 2014 and 22 Apr. 2015 as it survived the winter, as expected. There was no significant weed population present in the plots without a cover crop; therefore, no biomass was collected from those plots at the fall or spring samplings. The spring wheat test crop grain and straw were harvested on 18 Sept. 2014 and 13 Aug. 2015 by collecting the aboveground biomass from two 0.5 by 0.5 m quadrats per plot.

After plant harvesting, the biomass was placed in brown paper bags and oven-dried at 60°C for 7 d. The dry biomass was then determined and the samples were ground to pass through a 0.15-mm sieve. Total C and N in the cover crop and spring wheat biomass were determined by dry combustion (NA 1500 Series 2, Carlo Erba Instruments, Milan, Italy). The cover crop C and N concentrations from the 27 Nov. 2013 sampling was not measured due to the poor establishment of oilseed radish, so the N concentrations in the fall rye and oilseed radish tissues from the 6 Nov. 2014 sampling were used to estimate cover crop N uptake for fall 2013.

Statistical Analyses

All statistical analyses were computed with SAS 9.3 software (SAS Institute, Cary NC). Each year was separately analyzed. Residuals were checked for normality with the UNIVARIATE procedure. Repeated measures ANOVA was conducted with the MIXED procedure to assess the response of NH$_4$–N and NO$_3$–N concentrations to cover crop species (fall rye, oilseed radish, no cover crop) and nutrient source (compost, inorganic fertilizer) as a augmented 3 × 2 factorial plus a control (Marini, 2003). Cover crop species and nutrient source were fixed effects, block was a random effect, while time and depth were repeated measures for non-growing season NH$_4$–N and NO$_3$–N concentrations and pre-plant NH$_4$–N and NO$_3$–N, respectively. A similar mixed model was used for the cover crop biomass, cover crop N uptake, cover crop C/N ratios, and spring wheat grain yield and N uptake, but without a repeated measure. Significant differences between least square means were tested by Fisher’s protected LSD test at α < 0.05. The NLIN procedure was used for the nonlinear regression.

Table 2. Basic soil properties before amendment application (27 Aug. 2013 and 14 Aug. 2014).

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth</th>
<th>Total C</th>
<th>Total N</th>
<th>NO$_3$–N</th>
<th>NH$_4$–N</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>g C kg$^{-1}$</td>
<td>g N kg$^{-1}$</td>
<td>mg N kg$^{-1}$</td>
<td>mg N kg$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>0–7.5</td>
<td>21.3 ± 1.44†</td>
<td>1.7 ± 0.23</td>
<td>21.0 ± 10.20</td>
<td>2.7 ± 0.94</td>
<td>7.9 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>7.5–15</td>
<td>19.1 ± 1.65</td>
<td>1.6 ± 0.14</td>
<td>10.9 ± 4.20</td>
<td>2.5 ± 0.79</td>
<td>8.0 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>15–30</td>
<td>21.4 ± 4.06</td>
<td>1.1 ± 0.25</td>
<td>6.0 ± 3.05</td>
<td>2.5 ± 0.69</td>
<td>8.1 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>30–60</td>
<td>20.1 ± 5.21</td>
<td>0.6 ± 0.27</td>
<td>2.9 ± 1.89</td>
<td>2.8 ± 0.79</td>
<td>8.3 ± 0.16</td>
</tr>
<tr>
<td>2014</td>
<td>0–7.5</td>
<td>21.9 ± 1.51</td>
<td>1.7 ± 0.11</td>
<td>4.1 ± 2.36</td>
<td>2.5 ± 0.64</td>
<td>8.2 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>7.5–15</td>
<td>19.0 ± 2.35</td>
<td>1.4 ± 0.18</td>
<td>1.4 ± 0.90</td>
<td>2.3 ± 0.40</td>
<td>8.2 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>15–30</td>
<td>17.4 ± 4.25</td>
<td>1.1 ± 0.22</td>
<td>1.3 ± 1.07</td>
<td>2.1 ± 0.54</td>
<td>8.2 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>30–60</td>
<td>19.9 ± 5.58</td>
<td>0.8 ± 0.22</td>
<td>2.1 ± 3.11</td>
<td>2.5 ± 0.72</td>
<td>8.2 ± 0.12</td>
</tr>
</tbody>
</table>

† Mean value ± SD.
The mean (1981–2010) growing season (1 May–30 September) rainfall was 238 mm, while the mean temperature was 15.0°C. The 2014 growing season was 55% wetter than normal (370 mm) with slightly above normal mean daily temperature (15.5°C), while the 2015 growing season was 28% drier than normal (171 mm) with warmer than normal mean daily temperature (16.0°C). Precipitation data for the two experimental periods are provided in Fig. 1.

Throughout both non-growing seasons, fall rye significantly reduced soil NO₃–N concentrations compared with the soils planted with oilseed radish and amended soils with no cover crop (Fig. 2). Soil NO₃–N levels tended to be greater with oilseed radish compared with soil with no cover crop. In 2013–2014 the inorganically fertilized soil had 25% greater NO₃–N concentrations (mean 15.4 mg N kg⁻¹) over the non-growing season than the compost-amended soil (mean 12.3 mg N kg⁻¹). In 2014–2015, nutrient source had no significant effect on soil NO₃–N concentration during the non-growing season (Fig. 3). Between years there was about five times greater soil NO₃–N concentration in 2013–2014 than 2014–2015, mostly attributable to greater soil NO₃–N at the time of cover crop planting in August 2013 (Fig. 2). This could be related to previous fertilization history, or to greater precipitation in 2013–2014, leading to enhanced decomposition and mineralization.

NH₄–N concentrations were not significantly affected by cover crop or nutrient source in 2013–2014, while inorganically fertilized soil had significantly greater soil NH₄–N concentrations than the compost-amended soil with and without a cover crop in 2014–2015.

As oilseed radish dies over-winter, it likely decomposes more quickly than fall rye root tissues, supplying more labile N (Petersen et al., 2011; Mitchell et al., 2013), which could be mineralized and then oxidized by ammonia oxidizing and nitrifying microorganisms to NO₃–N over the non-growing season. In our study, the greater soil NO₃–N concentrations in the surface soil with oilseed radish than amended soils without a cover crop provides evidence that oilseed radish retains more N or results in more N turnover in the plant-soil system.
The latter may be explained by oilseed radish releasing antifungal isothiocyanates during its decomposition (White and Weil, 2010), which increases N turnover through fungal cell lysis or shifts in the microbial community structure. Applying isothiocyanate to soil increased bacterial and decreased fungal populations (Hu et al., 2015), but whether a reduction in fungal population translates into increased N supply is uncertain. Future research could investigate the mechanism driving this apparent increase in N availability with oilseed radish, as this labile N would be prone to N loss pathways.

Cover Crop Biomass and Quality

In fall 2013, the cover crop biomass was significantly affected by cover crop species (P < 0.001) but not nutrient source or cover crop species × nutrient source (Table 3). Fall rye produced three times more biomass than oilseed radish (1.5 vs. 0.5 Mg ha⁻¹), which translated into about 54 and 16 kg N uptake ha⁻¹ for fall rye and oilseed radish, respectively (P < 0.05). In the following spring, before planting spring wheat, there was about 2.7 Mg ha⁻¹ of aboveground biomass in the fall rye plots (Table 3). With C/N ratios of 17 and 14 with compost and inorganic fertilizer, respectively, fall rye biomass contained 71 and 118 kg N ha⁻¹ (Table 3). In fall 2014, cover crop species, nutrient source and cover crop species × nutrient source did not significantly affect cover crop biomass, N concentration, cover crop N uptake or the cover crop C/N ratio (Table 3).

The C/N ratios of the oilseed tops and taproots were not significantly affected by nutrient source in fall 2014 (P = 0.369 and 0.567, respectively). The oilseed radish taproots had greater C/N ratios than the tops. For the compost-amended soil, the oilseed radish taproots had a C/N ratio of 18, while the tops had a C/N ratio of 10. For the inorganically fertilized soils, the oilseed radish taproots had a C/N ratio of 22, while the tops had a C/N ratio of 12. On average, taproots accounted for 47% of total oilseed radish dry biomass, but the aboveground parts (53% of total biomass) had a more favorable C/N ratio for decomposition and mineralization. The taproot percentage (47%) of the total biomass (taproot plus shoot) measured in our study was greater than the 23 to 41% reported for oilseed radish in humid temperate regions (Chen and Weil, 2010; Jahanzad et al., 2016). This discrepancy may be related to water primarily limiting plant growth more in semiarid than humid temperate conditions, even given the 38 mm of irrigation water supplied for cover crop establishment in 2014. The tillage radish taproots may have preferentially elongated to draw water from deeper in the soil profile to compensate for the water deficit and thus exhibited a higher root/shoot ratio in our study.

Pre-Plant Soil Nitrate-Nitrogen and Ammonium-Nitrogen

In both years, pre-plant soil NO₃⁻N concentrations were affected by the cover crop species × depth interaction (Table 4, Fig. 4). Fall rye reduced soil NO₃⁻N concentrations compared with oilseed radish in all soil layers. Compared to amended soils with no cover crop, soils under oilseed radish had greater pre-plant NO₃⁻N in the top 7.5 cm soil layer in 2013–2014, and more pre-plant NO₃⁻N in the 0- to 15-cm soil layers in 2014–2015. In contrast to studies conducted with fodder radish in the Coastal Plain region of North America (Dean and Weil, 2009; Lacey and Armstrong, 2015), oilseed radish did not reduce NO₃⁻N levels at depth in our study. Both years, fall rye markedly reduced soil NO₃⁻N concentrations to the 60-cm depth compared with oilseed radish. The striking reduction in soil NO₃⁻N levels with fall rye clearly indicates that fall rye significantly reduces the risk of NO₃⁻N leaching. While leaching is not a primary concern in southern Alberta, extreme rainfall events (1 in 10 yr) do pose a risk for NO₃⁻N loss. On the other hand, soils cropped to tillage radish would be a higher risk for NO₃⁻N leaching under intense rainfall, which would increase the risk of N loss to surface and ground water. In 2013–2014, pre-plant NO₃⁻N was significantly affected by nutrient source (Table 4). Inorganically fertilized soils led to 21% greater pre-plant soil NO₃⁻N concentrations than the compost-amended soil in 2013–2014. Although the N application rates of the inorganically fertilized and compost-amended soils represent a significantly lower risk for NO₃⁻N leaching when applied at 100 kg total N ha⁻¹ compared with applying inorganic N fertilizer at 45 kg N ha⁻¹. This result is consistent
with soil fertilized with inorganic N fertilizer (calcium nitrate) increasing NO₃⁻N leaching by 4.4- to 5.6-fold compared with soil receiving composted chicken manure (Kramer et al., 2006). As the concentration of soil NO₃⁻N after amending soil with composted beef cattle manure is highly correlated (r = 0.97) to potential NO₃⁻N leaching (Li et al., 2016), the concentration increasing NO₃⁻N leaching by 4.4- to 5.6-fold compared with a fall rye cover crop. There was no evidence that fall rye decreased soil moisture in the following spring (data not shown), but our

data provide good evidence that the soil N supply, measured as pre-plant soil mineral N, was the principal limiting factor when spring wheat was grown after a fall rye cover crop, especially in 2013–2014 (Fig. 6). We cannot rule out that allelopathic effects contributed to the reduced vigor of spring wheat when preceded by fall rye as we did not monitor soil available N during while spring wheat grew. Regardless of the mechanism, which is probably a combination of complex interactions between characteristics of fall rye, soil and climatic properties and spring wheat (Thorup-Kristensen et al., 2003), in the present study, a fall rye cover crop reduced spring wheat grain yields by 38 to 57% compared to tillage radish or amended soil without a cover crop.

Although oilseed radish increased spring wheat grain yield the most each year, the gain was not significantly greater than that observed for the amended soils with no cover crop. However, in 2014 and 2015 there was a potential trend (P = 0.144 and 0.119, respectively) toward greater spring wheat grain yield with oilseed radish than amended soils with no cover crop. More research needs to be conducted to determine the potential benefit of oilseed radish in semiarid regions, in terms of nutrient and non-nutrient benefits. Williams and Weil (2004) reported the “biodrilling” phenomenon whereby oilseed radish taproots provided root channels for a subsequent soybean crop to access water deeper in the soil profile. In our study, the diameter of the oilseed radish taproots in 2014–2015 was not measured, but it was estimated that the diameter ranged from 1 to 5 cm, supporting that biodrilling was a

### Spring Wheat Grain Yield and Nitrogen Uptake

Both years, spring wheat grain yield was reduced by fall rye (Fig. 5, Table 3). Fall rye reduced spring wheat grain yield by 54 and 5% in 2013–2014 and by 38 and 50% in 2014–2015, relative to the amended soils with no cover crop and the soils planted with oilseed radish, respectively. This is consistent with Moyer and Blackshaw (2009) who found that fall rye reduced unfertilized spring wheat grain yield by 16 to 26% relative to soil with no cover crop in southern Alberta over three growing seasons. Moyer and Blackshaw (2009) suggested that the N supply to spring wheat was not limited by a preceding fall rye cover crop, but that allelopathic effects may be responsible; Duiker and Curran (2005) found no evidence of allelopathic effects and no reduction in corn (Zea mays L.) yield caused by a rye cover crop. There was no evidence that fall rye decreased soil moisture in the following spring (data not shown), but our

### Table 3. Cover crop aboveground dry biomass, N uptake and C/N ratio, fall rye spring biomass and N uptake, and spring wheat grain yield and N uptake in 2013–2014 and 2014–2015. In fall 2013, cover crop biomass was measured, but the C and N contents were not, so estimates of N uptake and C/N ratio were made using 2014–2015 data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fall cover crop sampling</th>
<th>Spring sampling</th>
<th>Wheat performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cover crop biomass</td>
<td>Cover crop N uptake</td>
<td>Cover crop C/N ratio</td>
</tr>
<tr>
<td></td>
<td>Mg ha⁻¹</td>
<td>kg N ha⁻¹</td>
<td></td>
</tr>
<tr>
<td>2013–2014</td>
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<tr>
<td>Cover crop</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fall rye</td>
<td>1.5a</td>
<td>54</td>
<td>12</td>
</tr>
<tr>
<td>Fertilizer source</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Compost</td>
<td>1.0</td>
<td>35</td>
<td>11</td>
</tr>
<tr>
<td>Inorganic</td>
<td>1.0</td>
<td>33</td>
<td>12</td>
</tr>
<tr>
<td>Source of variation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover crop (CC)</td>
<td>&lt;0.001</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Nutrient source (NS)</td>
<td>0.768</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>CC × NS</td>
<td>0.640</td>
<td>nd</td>
<td>nd</td>
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<td>2014–2015</td>
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<tr>
<td>Cover crop</td>
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<tr>
<td>Fall rye</td>
<td>1.2</td>
<td>42</td>
<td>12</td>
</tr>
<tr>
<td>Fertilizer source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compost</td>
<td>1.2</td>
<td>42</td>
<td>11</td>
</tr>
<tr>
<td>Inorganic</td>
<td>1.2</td>
<td>39</td>
<td>12</td>
</tr>
<tr>
<td>Source of variation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover crop (CC)</td>
<td>0.833</td>
<td>0.844</td>
<td>0.568</td>
</tr>
<tr>
<td>Nutrient source (NS)</td>
<td>0.985</td>
<td>0.725</td>
<td>0.322</td>
</tr>
<tr>
<td>CC × NS</td>
<td>0.518</td>
<td>0.950</td>
<td>0.357</td>
</tr>
</tbody>
</table>

† na, not applicable; nd, not determined.
ANOVA 2017 Volume

In 2014 and 2015 and nutrient source in 2014 (Table 3). In 2014, compost (2.7 Mg ha–1). Nutrient source did not have a significant effect on spring wheat grain yield in 2014–2015 (Table 3), suggesting that soil N was immobilized in the fall rye biomass during the non-growing season, and also during its decomposition in the following spring.

The inorganically fertilized (32 kg N ha–1) and composted-amended soil (33 kg N ha–1) produced similar spring wheat grain N uptake. The control soil led to spring wheat grain N uptake 45 kg N ha–1 lower with fall rye than normal. This indicates that moisture was probably less limiting which shifted the limitation toward plant-available N.

Spring wheat grain N uptake was affected by cover type in 2014 and 2015 and nutrient source in 2014 (Table 3). In 2014, fall rye led to lower spring wheat grain N uptake (37 kg N ha–1) than amended soils without a cover crop (94 kg N ha–1) and amended soils with oilseed radish (104 kg N ha–1). Spring wheat grain N uptake was greater with inorganically fertilized (85 kg N ha–1) than composted-amended (71 kg N ha–1) soils (Table 3). The nutrient sources are difficult to apply at the same plant-available N rate given the large organic-N fraction in compost. However, we only observed a significant nutrient source effect during the growing season with 55% greater rainfall than normal. This indicates that moisture was probably less limiting which shifted the limitation toward plant-available N.
Fall rye effectively scavenged N over the non-growing season, which is consistent with research that showed fall rye decreased NO$_3$–N levels in Iowa (Parkin and Kaspar, 2006). However, slow decomposition appeared to limit the soil N supply for spring wheat. Research has shown that the decomposition of perennial grasses occurs more slowly than annual grasses (Shi et al., 2013). This is likely a direct reflection of more lignified tissue in the perennial grasses, which has been directly linked to slower fall rye decomposition (Neely et al., 1991). For example, fall rye released only 10% of the N it contained over a 3-mo period (Beare et al., 1992). Although greater lignification has been linked to slower biotic decomposition (Whalen et al., 2014), it accelerated photodegradation (Austin and Ballaré, 2010). Future research could investigate the role of photodegradation vs. biotic decomposition in semiarid agroecosystems to determine the magnitude of these processes in the regulation of litter decomposition. Research has indicated that the structural and chemical bottleneck induced by lignin content in litter can be “photoprimed” by UV radiation to enhance microbial decomposition processes (Austin et al., 2016). Further understanding these processes could assist in appropriately timing the fall rye kill date and improving the synchrony between cover crop N supply and crop N demand.

A strong quadratic relationship was found between pre-plant soil NH$_4$–N plus NO$_3$–N level and spring wheat grain yield (Fig. 4). In 2015, soil NH$_4$–N plus NO$_3$–N levels were <5 mg N kg$^{-1}$ in the top 15 cm of soil, suggesting that soil N availability was low that year. This supports our finding that wheat yields were generally two to three times lower in 2015 than in 2014 for all treatments (Fig. 3). Because of the narrow range of pre-plant soil NH$_4$–N plus NO$_3$–N concentrations (3.5–5 mg N kg$^{-1}$) in spring 2015, no clear relationship could be established with spring wheat grain yield, suggesting that maximized yields could not be reached. However, the differences among treatments appeared consistent between years (Fig. 3). The dotted line in (a) and (b) indicates the spring wheat grain yield in the control (no amendment, no cover crop).
Fig. 6. The functional relationship between pre-plant soil NO$_3$–N plus NH$_4$–N concentration (14 May 2014) in the 0- to 7.5-cm soil layer and spring wheat grain yield in response to late-summer-seeded cover crops and nutrient source in Lethbridge, AB. FRF, fall rye with inorganic fertilizer; ORC, oilseed radish with inorganic fertilizer; ORF, oilseed radish with composted beef cattle manure; CON, no cover crop with inorganic fertilizer; NCF, no cover crop with composted beef cattle manure; NCC, no cover crop with manure; FRF, fall rye with composted beef cattle manure; ORC, oilseed radish with inorganic fertilizer; ORF, oilseed radish with inorganic fertilizer; NCC, no cover crop with composted beef cattle manure; NCF, no cover crop with inorganic fertilizer; CON, non-amended control soil with no cover crop.

No NO$_3$–N levels therefore appear to be a potential predictor of wheat yield in the studied area. Given that the growing season in 2014 had 55% above normal precipitation, it appears that this pre-plant measurement also is an indicator of organic-N mineralization as decomposition and mineralization processes would be less constrained under these wetter conditions.

Although we applied some irrigation water to establish the cover crops, no irrigation water was applied to the spring wheat in either year. While it is an uncommon practice to irrigate a cover crop but not the succeeding crop, we thought it was necessary to help establish the cover crops from an experimental standpoint. Fall rye clearly reduced soil NO$_3$–N levels, indicating its utility as a N scavenging cover crop, but the apparent asynchrony between the release of N from its biomass and spring wheat N uptake raises questions about its agronomic value, and how it can be optimally used. This is especially important for dryland crop production in semiarid regions where precipitation often limits crop yield more than N or P (Hao et al., 2016). If fall rye is to be utilized as a cover crop in this semiarid region for dryland crop production, supplemental fertilizer N in the following spring is likely required to offset its limited N release, which increases the risk N will be over-applied. In contrast, oilseed radish would require less or no fertilizer N application, depending on the pre-plant NH$_4$–N plus NO$_3$–N concentration and the subsequent growing season precipitation. Alternatively, terminating a fall rye cover crop earlier in the spring or possibly even in the fall after establishment, and allowing the photodegradation and biotic decomposition processes to begin may be another strategy to enhance synchrony between the cover crop N supply and crop N demand, and reduce the amount of supplemental N required. In our study, we killed fall rye 13 or 22 d before planting spring wheat, and given the poor agronomic performance of spring wheat, this may have been too late.

To avoid N immobilization with a cereal rye cover crop in northeastern United States, Ketterings et al. (2015) recommended delaying corn planting by 2 to 3 wk after cover crop termination and applying supplemental fertilizer N. If supplemental fertilizer N was applied to compensate for the limited N release from fall rye, seeding fall rye post-harvest may retain surplus N from the fertilizer N application, and thus mitigate the risk of the supplemental N fertilizer losses. Other previous studies have found that 2 wk between the kill date of a vetch–cereal rye mix (Clark et al., 1994) or cereal rye (Wagner-Riddle et al., 1994; Raimbult et al., 1991; Clark et al., 1997) and the cash crop planting date did not affect crop yield. Furthermore, fall rye grown to the early- to late-boot stage and killed 7 to 10 d before planting corn did not reduce corn yield (Duiker and Curran, 2005). However, the above work was conducted in a humid temperate climate, where decomposition and mineralization occur faster than semiarid climates (Helgason et al., 2014). Limited research has been conducted on cover crops in semiarid regions (Liebig et al., 2015), which represents a large knowledge gap. Although the timing of the fall rye kill was not an objective of this study, future research could investigate how the timing of fall rye termination impacts the soil N supply and crop yields in semiarid regions.

While regular N leaching events are not a primary concern with respect to N loss from agroecosystems in semiarid regions, increasing crop yield is. Our data provide evidence that oilseed radish may boost crop yields, while supplemental N may be required with fall rye to avoid significant reductions in the succeeding crop’s yield. On average, the growing season has increased by 6 to 10 d in southern Alberta over the past 100 yr (Qian et al., 2012). As the growing season is expected to continue increasing in length, optimizing cover crop management practices will be important to minimize wind erosion and enhance nutrient use efficiency. Overall, cover crop management is complex because the benefits of soil conservation, especially near Lethbridge where winds are ≥40 km h$^{-1}$ 116 d per year, are difficult to quantify. While wheat grain yield can be clearly quantified, it is much more difficult to measure the benefits of cover crops, and this may result from most studies taking a reductionist approach to studying cover crops (e.g., focusing too narrowly on soil physical, chemical or biological properties vs. the whole system). It should be recognized that cover cropping may require enhanced nutrient management to ensure that the benefits of cover crops from a soil conservation perspective are balanced with crop yields that meet the objectives of the producer. More studies are required so that the benefits of soil conservation, surface and groundwater protection, and enhanced biodiversity are more clearly recognized in cover cropped soils, while the potential for increased nutrient management is acknowledged as a possible downside but efficiently manageable aspect of cover cropping.

**CONCLUSIONS**

Fall rye more effectively scavenged and retained N than oilseed radish during the two non-growing seasons, but did not supply sufficient N to the succeeding dryland spring wheat crop. Dryland spring wheat grain yields after a fall rye cover crop were reduced by 38 to 57% compared with amended soils with no cover crop and soil planted with oilseed radish. Based
on our 2-yr study, fall rye must be carefully managed because the N it retained was not transferred to the succeeding crop, which means extra fertilizer N would be required to account for this apparent deficit. Otherwise, the kill date of fall rye must be better understood in semiarid regions where moisture levels constrain microbial mediated decomposition and mineralization of crop residues. Oilseed radish is known for passing on non-nutrient benefits to succeeding crops and appeared to adequately decompose and mineralize to supply more N than fall rye for the subsequent spring wheat crop. Compost-amended soils were a lower risk for pre-plant NO3–N accumulation than inorganically fertilized soils in 2014, while inorganically fertilized soils led to 10% greater spring wheat grain yield and 19% greater N uptake than compost-amended soils. This indicates the N release was too slow from compost, even with growing season rainfall 55% greater than normal. Measuring pre-plant soil NO3–N plus NH4–N levels in the spring following a cover crop is a good practice to determine whether supplemental N is needed to reach adequate yield for succeeding crops, especially in dryland crop production whereby moisture can limit crop growth more than N, and restrict N use efficiency.

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REFERENCES


