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# Soil residual nitrogen under various crop rotations and cultural practices

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Crop rotation and cultural practice may influence soil residual N available for environmental loss due to crop N uptake and N immobilization. We evaluated the effects of stacked *vs*. alternate-year crop rotations and cultural practices on soil residual N (NH4-N and NO3-N contents) at the 0–125 cm depth, annualized crop N uptake, and N balance from 2005 to 2011 in the northern Great Plains, USA. Stacked rotations were durum (*Triticum turgidum* L.)–durum–canola (*Brassica napus*L.)–pea (*Pisum sativum* L.) (DDCP) and durum–durum–flax (*Linum usitatissimum* L.)–pea (DDFP). Alternate-year rotations were durum–canola–durum–pea (DCDP) and durum–flax–durum–pea (DFDP). Both of these are legume-based rotations because they contain legume (pea) in the crop rotation. A continuous durum (CD) was also included for comparison. Cultural practices were traditional (conventional tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height) and improved (no-tillage, increased seeding rate, banded N fertilization, and increased stubble height) systems. The amount of N fertilizer applied to each crop in the rotation was adjusted to soil NO3-N content to a depth of 60 cm observed in the autumn of the previous year. Compared with other crop rotations, annualized crop biomass N was greater with DCDP and DDCP in 2007 and 2009, but was greater with DDFP than DCDP in 2011. Annualized grain N was greater with DCDP than CD, DFDP, and DDFP and greater in the improved than the traditional practice in 2010 and 2011. Soil NH4-N content was greater with CD than other crop rotations in the traditional practice at 0–5 cm, but was greater with DDCP than CD and DDFP in the improved practice at 50–88 cm. Soil NO3-N content was greater with CD than other crop rotations at 5–10 cm, but was greater with CD and DFDP than DCDP and DDCP at 10–20, 88–125, and 0–125 cm. Nitrate-N content at 88–125 and 0–125 cm was also greater in the traditional than the improved practice. Nitrogen balance based on the difference between N inputs and outputs was greater with crop rotations than CD. Increased N fertilization rate increased soil residual N with CD, but legume N fixation increased N balance with crop rotations. Legume-based crop rotations (all rotations except CD) reduced N input and soil residual N available for environmental loss, especially in the improved practice, by increasing crop N uptake and N immobilization compared with non-legume monocrop.

**Keywords**

crop nitrogen, soil inorganic nitrogen, management practice, nitrogen balance

**Disciplines**

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# Soil residual nitrogen under various crop rotations and cultural practices

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## Abstract

Crop rotation and cultural practice may influence soil residual N available for environmental loss due to crop N uptake and N immobilization. We evaluated the effects of stacked *vs*. alternate-year crop rotations and cultural practices on soil residual N ($NH_4$-N and $NO_3$-N contents) at the 0–125 cm depth, annualized crop N uptake, and N balance from 2005 to 2011 in the northern Great Plains, USA. Stacked rotations were durum (*Triticum turgidum* L.)–durum–canola (*Brassica napus* L.)–pea (*Pisum sativum* L.) (DDCP) and durum–durum–flax (*Linum usitatissimum* L.)–pea (DDFP). Alternate-year rotations were durum–canola–durum–pea (DCDP) and durum–flax–durum–pea (DFDP). Both of these are legume-based rotations because they contain legume (pea) in the crop rotation. A continuous durum (CD) was also included for comparison. Cultural practices were traditional (conventional tillage, recommended seeding rate, broadcast N fertilization, and reduced stubble height) and improved (no-tillage, increased seeding rate, banded N fertilization, and increased stubble height) systems. The amount of N fertilizer applied to each crop in the rotation was adjusted to soil $NO_3$-N content to a depth of 60 cm observed in the autumn of the previous year. Compared with other crop rotations, annualized crop biomass N was greater with DCDP and DDCP in 2007 and 2009, but was greater with DDFP than DCDP in 2011. Annualized grain N was greater with DCDP than CD, DFDP, and DDFP and greater in the improved than the traditional practice in 2010 and 2011. Soil $NH_4$-N content was greater with CD than other crop rotations in the traditional practice at 0–5 cm, but was greater with DDCP than CD and DDFP in the improved practice at 50–88 cm. Soil $NO_3$-N content was greater with CD than other crop rotations at 5–10 cm, but was greater with CD and DFDP than DCDP and DDCP at 10–20, 88–125, and 0–125 cm. Nitrate-N content at 88–125 and 0–125 cm was also greater in the traditional than the improved practice. Nitrogen balance based on the difference between N inputs and outputs was greater with crop rotations than CD. Increased N fertilization rate increased soil residual N with CD, but legume N fixation increased N balance with crop rotations. Legume-based crop rotations (all rotations except CD) reduced N input and soil residual N available for environmental loss, especially in the improved practice, by increasing crop N uptake and N immobilization compared with non-legume monocrop.

**Key words:** crop nitrogen / soil inorganic nitrogen / management practice / nitrogen balance

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## 1 Introduction

Inefficient N uptake by crops due to application of N fertilizers, manures, and other amendments results in accumulation of soil residual N ($NO_3$-N + $NH_4$-N) after crop harvest (*Varvel* and *Peterson*, 1990). As crops can remove about 40 to 60% of applied N, the residual N after crop harvest can be lost to the environment through leaching, denitrification, volatilization, surface runoff, soil erosion, and $N_2O$ emissions (*Smil*, 1999; *Janzen* et al., 2003; *Eickhout* et al., 2006; *Ross* et al., 2008). Nitrogen-use efficiency for crops can be further reduced at high N fertilization rates. *Varvel* and *Peterson* (1990) have reported that N removed by corn (*Zea mays* L.) or sorghum (*Sorghum bicolor* [L.] Moench) grain accounted for 50% of the applied N at low N rates and 20 to 30% at high N rates. Therefore, improved management practices are needed to reduce N fertilization rates and soil residual N by enhancing N-use efficiency while maintaining crop yields and quality. Producers are increasingly interested in reducing the amounts of N fertilizers applied to crops because of higher costs of N fertilization and the associated environmental degradation.

One of the ways to reduce N fertilization rates to crops while maintaining yield goals is to account for soil residual N at crop planting and N mineralized from soil organic matter during the crop growing season (*Schepers* and *Mosier*, 1991). About 1–2% of soil organic N to a depth of 30 cm is mineralized every year, depending on soil temperature and water content, residue addition (fresh or old residue), and soil organic matter

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(*Schepers* and *Mosier*, 1991; *Wang* et al., 2014). It is not practical to measure N mineralization potential of the soil at crop planting due to excessive time required for soil analysis. A cost-effective and commonly used practice in the semiarid regions of northern Great Plains, USA, to determine N rates for crops is to test $NO_3$-N content in soil samples collected to a depth of 60 cm after crop harvest in the autumn of the previous year and deduct this value from recommended N rates for succeeding crops (*Miller* et al., 2002; *Lenssen* et al., 2007; *Sainju* et al., 2014). It is assumed that N losses to the environment due to N leaching, volatilization, and denitrification from soil residual N during the winter are minimal due to cold weather and limited precipitation.

Legume-based crop rotations provide opportunity to reduce N fertilizer rates due to N supplied by legumes to succeeding crops compared with non-legume monocrops (*Varvel* and *Peterson*, 1990; *Clayton* et al., 2004; *MacWilliams* et al., 2014). Furthermore, little or no N fertilizer are applied to legumes during their growth, which helps to reduce overall N rates for a crop rotation. As a result, farmers can increase farm income and reduce C footprints (*Gan* et al., 2011; *MacWilliams* et al., 2014). Legumes can release N for as long as three years, thereby increasing yields of succeeding crops compared with non-legumes (*Lupwayi* and *Soon*, 2016). Other benefits of crop rotation include reduced disease, pest, and weed infestations (*Stevenson* and *van Kessel*, 1996), increased water-use efficiency (*Miller* et al., 2003), improved soil structure and organic matter (*Chan* and *Heenan*, 1991; *Bremer* et al., 2008), and enhanced soil health due to increased microbial biomass and activity (*Lupwayi* and *Kennedy*, 2007; *Trabelsi* et al., 2012). Crop rotation can also reduce soil residual N compared with monocropping due to increased N uptake by crops (*Varvel* and *Peterson*, 1990; *Clayton* et al., 2004; *MacWilliams* et al., 2014).

Stacked crop rotations in which the same crop is grown successively for a number of years in rotation with other crops can reduce disease, weed, and pest infestations compared with alternate-year rotations (*Garrison* et al., 2014; *Nickel*, 2014). Weeds compete with each other in a similar environment for a longer period of time in these rotations and residual herbicides can be used in the first year for effective control of weeds (*Garrison* et al., 2014). Weeds can also be effectively controlled by using improved cultural practices in which higher crop seeding rates, banded N fertilization, and delayed planting and harvest are employed compared with recommended seeding rates, broadcast N fertilization, and early planting and harvest in the traditional practices (*Strydhorst* et al., 2008; *Nichols* et al., 2015). No-tillage in the improved practice, however, can increase weed growth and reduce N mineralization compared with conventional tillage in the traditional practice, but application of proper herbicides can control weeds in the no-tillage system (*Lenssen* et al., 2007; *Sainju* et al., 2015). The effects of stacked *vs*. alternate-year crop rotations and continuous monocropping as well as alteration in cultural practices on N input, soil residual N, crop N uptake, and N balance, however, are lacking.

We examined the effects of stacked and alternate-year crop rotations and monocropping under traditional and improved cultural practices on soil residual N, crop N uptake, N input, and N balance from 2005 to 2011 in eastern Montana, USA. Our objectives were to: (1) evaluate the effects of crop rotation and cultural practice on soil residual N and crop N uptake, (2) calculate N balance based on N inputs and outputs, and (3) determine which crop rotations and cultural practices reduce N fertilization rate and soil residual N while sustaining crop N uptake and environmental quality. We hypothesized that alternate-year crop rotations with the improved cultural practice would reduce N fertilization rate and soil residual N and enhance crop N uptake with minimal N loss to the environment compared with other treatments.

## 2 Material and methods

### 2.1 Experimental site and treatments

The experiment was conducted from 2005 to 2011 in a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustoll) with 2% slope at the USDA Conservation District Farm, 11 km north of Culbertson, Montana, USA. At the initiation of the experiment in April 2005, the soil at the 0–15 cm depth had 660 g $kg^{-1}$ sand, 180 g $kg^{-1}$ silt, 160 g $kg^{-1}$ clay, 10.1 g $kg^{-1}$ soil organic C, 7.2 pH, and 1.27 Mg $m^{-3}$ bulk density. Mean monthly air temperature (115-y average) at the study site ranges from –8°C in January to 33°C in July and August and a mean annual precipitation of 341 mm, 70% of which occurs during the growing season (April to August). Cropping history for 12 y before the experiment initiation was continuous durum under conventional tillage.

Treatments were two cultural practices as the main plot and five crop rotations as the split-plot factor arranged in a randomized complete block design with three replications. Crop rotations included 4-y rotations of two stacked and two alternate-year crop rotations and one monocropping. Stacked rotations included durum–durum–canola–pea (DDCP) and durum–durum–flax–pea (DDFP), alternate-year rotations included durum–canola–durum–pea (DCDP) and durum–flax–durum–pea (DFDP), and monocropping included continuous durum (CD). The sequence of crops grown in each rotation is shown in Tab. 1. The number of plots was 1 for CD, where only one crop was grown, and four in other rotations, where four crops (one crop in each plot) were grown in a year. All crops in each rotation were present in every year. In the following years, crops were switched in the plots in a rotation system to complete the 4-y cycle in 4 y. Because of limited precipitation (341 mm annual precipitation) and cold winter, only one crop can be grown in the summer (April–August) in a year in this region. Cultural practices were traditional and improved practices that included combinations of various tillage practices, seeding rates, N fertilization rates and methods, and stubble heights at crop harvest for durum, pea, canola, and flax (Tab. 2). Conventional tillage in the traditional practice included tilling the plots in the spring before crop planting with a field cultivator to a depth of 7 to 8 cm for seedbed preparation and weed control. No-tillage in the improved practice included leaving the plots undisturbed, except during planting and fertilization with a no-till planter in crop rows. Main plot size was 204 m × 18 m and split plot size varied from 12 m × 18 m for

CD to 48 m × 18 m for DCDP, DDCP, DFDP, and DDFP, each within two cultural practices. The variations in split plot size among crop rotations within each main plot were due to number of plots in the rotation (Tab. 1). For example, monocropping CD had only one plot, but other 4-y rotations had 4 plots where each crop appeared in every year.

## 2.2 Crop management

From 2005 to 2011, canola and pea were planted in early to mid-April, durum in late April, and flax in late April to early May in each year (Tab. 2). A no-till drill equipped with low-disturbance Barton double-shoot disk openers on 20-cm centers was used for planting and fertilization. At planting, N at various rates (Tab. 2) was applied as urea (46% N) and monoammonium phosphate (11% N, 23% P). For canola, N from ammonium sulfate (21% N, 24% S) was also used, which supplied 27 kg S ha$^{-1}$. Pea received N from monoammonium phosphate while applied as a P fertilizer. Yield goals of 1402 kg ha$^{-1}$ for canola and flax and 2355 kg ha$^{-1}$ for durum were employed while applying N fertilizers. Nitrogen fertilization rates to crops were adjusted for soil residual $NO_3$-N content. For this, soil $NO_3$-N content to a depth of 60 cm after crop harvest measured in the autumn of the previous year was deducted from desired N rates. Nitrogen fertilizers were broadcast and incorporated to a depth of 8 cm into the soil due to tillage in the traditional practice and banded to a depth of 5 cm below and 5 cm to the side of the seed in the improved practice. At planting, P from monoammnium phosphate at 29 kg P ha$^{-1}$ and K from muriate of potash (52% K) at 27 kg K ha$^{-1}$ were banded as above to all crops. Weeds were controlled with selective post emergence labeled herbicides appropriate for each crop. Contact herbicides were applied at postharvest and preplanting. No irrigation was applied.

Aboveground total biomass (grains, stems, and leaves) yield of all crops was determined in late July and August of each year by collecting biomass from two 0.5 m$^2$ areas outside yield rows, oven-drying at 55°C for 7 d, and weighing. At the same time, grain yield was determined by using a plot combine from an area of 6 m × 16 m from central rows of the split plot, oven-drying at 55°C for 7 d, cleaning, and weighing. Subsamples of biomass and grain were ground to 1 mm for determination of N concentration (g N kg$^{-1}$) using a high combustion C and N analyzer (LECO, St. Joseph, MI). Nitrogen uptake (kg N ha$^{-1}$) in each component was determined by multiplying total biomass and grain yields by their N concentrations. Aboveground biomass (stems and leaves) N uptake was determined by deducting grain N from total biomass N. After grain harvest, biomass residue of all crops was returned to the soil.

**Table 1**: Crops planted in stacked and alternate-year rotations and monocropping within traditional and improved cultural practices from 2005 to 2011.

| Crop rotation[a] | Number of plots | Crops planted in various years | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
| CD | 1 | Durum | Durum | Durum | Durum | Durum | Durum | Durum |
| DCDP | 1 | Durum | Canola | Durum | Pea | Durum | Canola | Durum |
| | 2 | Canola | Durum | Pea | Durum | Canola | Durum | Pea |
| | 3 | Durum | Pea | Durum | Canola | Durum | Pea | Durum |
| | 4 | Pea | Durum | Canola | Durum | Pea | Durum | Canola |
| DDCP | 1 | Durum | Durum | Canola | Pea | Durum | Durum | Canola |
| | 2 | Durum | Canola | Pea | Durum | Durum | Canola | Pea |
| | 3 | Canola | Pea | Durum | Durum | Canola | Pea | Durum |
| | 4 | Pea | Durum | Durum | Canola | Pea | Durum | Durum |
| DFDP | 1 | Durum | Flax | Durum | Pea | Durum | Flax | Durum |
| | 2 | Flax | Durum | Pea | Durum | Flax | Durum | Pea |
| | 3 | Durum | Pea | Durum | Flax | Durum | Pea | Durum |
| | 4 | Pea | Durum | Flax | Durum | Pea | Durum | Flax |
| DDFP | 1 | Durum | Durum | Flax | Pea | Durum | Durum | Flax |
| | 2 | Durum | Flax | Pea | Durum | Durum | Flax | Pea |
| | 3 | Flax | Pea | Durum | Durum | Flax | Pea | Durum |
| | 4 | Pea | Durum | Durum | Flax | Pea | Durum | Durum |

[a]Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

**Table 2**: Description of cultural practices (traditional and improved) used for crops in the rotation.

| Crop | Cultural practice | Tillage | Seeding rate (kg ha$^{-1}$) | N fertilization rate (kg N ha$^{-1}$) | Method of N fertilization | Planting date | Harvest date | Stubble height (cm) |
|---|---|---|---|---|---|---|---|---|
| Durum | traditional | conventional till | 90 | 127 | broadcast | late April | early to mid-August | 19 |
| | improved | no till | 120 | 127 | banded | late April | early to mid-August | 33 |
| Pea | traditional | conventional till | 101 | 6 | broadcast | early April | late July | 5 |
| | improved | no till | 140 | 6 | banded | early April | late July | 5 |
| Canola | traditional | conventional till | 6 | 94 | broadcast | mid-April | early to mid-August | 19 |
| | improved | no till | 9 | 94 | banded | mid-April | early to mid-August | 19 |
| Flax | traditional | conventional till | 34 | 58 | broadcast | early May | mid to late August | 13 |
| | improved | no till | 50 | 58 | banded | early May | mid to late-August | 13 |

## 2.3 Soil sample collection and analysis

In April 2005, October 2006, October 2008, and October 2011, soil samples were collected to a depth of 125 cm to determine $NH_4$-N and $NO_3$-N concentrations. Using a truck-mounted hydraulic probe (3.5 cm inside diameter), samples were collected from five places (in and between rows) in the central rows of each plot, separated into 0–5, 5–10, 10–20, 20–50, 50–88, and 88–125-cm depth increments, and composited within a depth. Soil samples were air-dried, ground after removing crop residue, coarse root, and stone fragments, and sieved to 2 mm. The $NH_4$-N and $NO_3$-N concentrations (mg N kg$^{-1}$) in soil samples were determined by extracting samples with 2 mol L$^{-1}$ KCl for 1 h and analyzing the extract colorimetrically with an autoanalyzer (Lachat Instruments, Loveland, CO), where $NH_4$-N was determined using the indophenol blue reaction and $NO_3$-N was reduced to $NO_2$-N using Cd reduction and quantified using a modified Griess–Ilosvay method (*Mulvaney*, 1996). A separate undisturbed core sample (3.5 cm inside diameter) was taken from each depth and year to determine the soil bulk density. The core sample was oven-dried at 105°C for 24 h and weighed, from which the bulk density was determined by dividing the weight of the oven-dried soil by the volume of the core. The $NH_4$-N and $NO_3$-N contents (kg N ha$^{-1}$) in soil samples at each depth and year were determined by multiplying their concentrations by the bulk density and the thickness of the soil layer. The $NH_4$-N and $NO_3$-N contents at 0–125 cm were determined by summing the contents from individual soil layers.

Nitrogen balance (NB) was calculated as:

$$NB = N_a + N_b + N_c - N_d - N_e, \tag{1}$$

where $N_a$ = soil residual N ($NH_4$-N + $NO_3$-N) content in 2005, $N_b$ = total N fertilization rates to crops from 2005 to 2011, $N_c$ = total pea N fixation from 2005 to 2011, $N_d$ = total crop grain N removal from 2005 to 2011, and $N_e$ = soil residual N ($NH_4$-N + $NO_3$-N) content in 2011. Biological N fixed by pea ($N_c$) was calculated as:

$$N_c = 0.7 \times (\text{aboveground pea biomass N} + 0.33 \times \text{aboveground total pea biomass N}), \tag{2}$$

where *0.7* is the conversion factor for N fixed by pea, assuming that 70% of N is fixed by legumes and 30% is taken up from the soil (*Meisinger* and *Randall*, 1991; *Ross* et al., 2008; *Pieri* et al., 2011). The value *0.33 × aboveground total pea biomass N* refers to belowground biomass N, assuming that belowground biomass N constitutes about one-third of the total aboveground biomass N (*Meisinger* and *Randall*, 1991). It was assumed that N inputs from atmospheric N deposition, crop seeds, and non-symbiotic N fixation are negligible.

## 2.4 Data analysis

Data for crop biomass and grain N uptake, soil $NH_4$-N and $NO_3$-N contents at a depth, and N balance were analyzed using the SAS-MIXED model (*Littell* et al., 2006). Cultural practice (main plot treatment), crop rotation (split-plot treatment), and their interaction were considered as fixed effects, replication and cultural practice × replication as random effects, and year as the repeated measure variable. Because each phase of the crop rotation was present in every year, data for phases were averaged within a rotation and the averaged value (annualized crop biomass and grain N and soil $NH_4$-N and $NO_3$-N contents) was used for a rotation for the analysis. Means were separated by using the least square means test when treatments and interactions were significant (*Littell* et al., 2006). Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

# 3 Results and discussion

## 3.1 Annualized crop biomass and grain nitrogen uptake

Annualized crop biomass and grain N uptake varied with crop rotations and years (Tab. 3). Significant interactions occurred for crop rotation × year for biomass N uptake and cultural practice × year for grain N uptake. Averaged across cultural practices, biomass N uptake was greater with DCDP and DDCP than CD, DFDP, and DDFP in 2007 (Tab. 4). Biomass N uptake was greater with DCDP than CD in 2009, but was greater with DDFP than DCDP in 2011. Averaged across cultural practices and years, biomass N uptake was greater with DCDP and DDCP than other crop rotations (Tab. 3). Averaged across crop rotations and cultural practices, biomass N uptake was greater in 2006 than other years.

During the dry year in 2007, when the growing season precipitation (April–August) was 20 mm below the 115-y average (Fig. 1), durum had poor growth with CD, resulting in lower biomass N uptake with this treatment (Tab. 4). Growth of durum, canola, and pea, however, remained stable in crop rotations, resulting in greater biomass N uptake with DCDP and DDCP. This also occurred in 2009, when the growing season precipitation was 54 mm above the average. Increased growth of flax increased biomass N uptake with DDFP in 2011, when the growing season precipitation was 99 mm above the average. Because of higher N concentration in pea residue than other crop residues (22–25 g N $kg^{-1}$ in pea residue compared with 8 to 16 g N $kg^{-1}$ in other crop residues) and increased N mineralization, greater N supplied by pea residue likely increased durum and canola biomass N uptake, thereby increasing biomass N uptake with DCDP and DDCP than other crop rotations, regardless of cultural practices and years. Increased crop yields and N uptake with legume-based crop rotations compared with non-legume monocropping had been previously reported (*Varvel* and *Peterson*, 1990; *Clayton* et al., 2004; *MacWilliams* et al., 2014).

**Table 3**: Effects of crop rotation and year on annualized crop biomass (stems and leaves) and grain N uptake.

| **Crop rotation**[a] | **Year** | **Annualized biomass N uptake (kg N $ha^{-1}$)**[bc] | **Annualized grain N uptake (kg N $ha^{-1}$)** |
|---|---|---|---|
| CD | | 57.2c | 50.5d |
| DCDP | | 76.1a | 63.5a |
| DDCP | | 74.5a | 60.5ab |
| DFDP | | 64.1bc | 58.3bc |
| DDFP | | 67.6b | 54.5cd |
| | 2005 | 38.5d | 63.4b |
| | 2006 | 102.2a | 36.5d |
| | 2007 | 73.1b | 54.6cd |
| | 2008 | 58.8c | 52.5cd |
| | 2009 | 61.8c | 62.9b |
| | 2010 | 82.5b | 73.1a |
| | 2011 | 58.4c | 59.4bc |
| Significance | | F values and significance level | |
| Crop rotation (R) | | 7.49*** | 4.76*** |
| Cultural practice (C) | | 1.04 | 1.49 |
| R × C | | 0.83 | 0.86 |
| Year (Y) | | 43.84*** | 19.93*** |
| R × Y | | 4.06*** | 1.37 |
| C × Y | | 1.05 | 2.17* |
| R × C × Y | | 0.41 | 0.31 |

[a] Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.
[b] * and *** significant at $P = 0.05$ and 0.001, respectively.
[c] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

Annualized crop grain N uptake, averaged across crop rotations, was greater in the improved than the traditional practice in 2010 and 2011 (Tab. 4), when the growing season precipitation was 99 to 182 mm above the average. Enhanced water conservation with no-tillage likely increased grain yield and therefore N uptake in the improved practice during years with above-average precipitation compared with conventional tillage where soil is disturbed. No-tillage can conserve soil water better than conventional tillage due to reduced soil disturbance and increased residue accumulation at the soil surface and increase dryland crop yields (*Farahani* et al., 1998; *Halvorson* et al., 1999). Increased seeding rate, banded N fertilization, and reduced light interception due to tall stubble height reduce weed growth in the improved practice compared with recommended seeding rate, broadcast N fertilization, and short stubble height in the conventional practice, thereby favoring crop growth in the improved practice (*Strydhorst* et al., 2008; *Garrison* et al., 2014; *Lenssen* et al., 2014).

Averaged across cultural practices and years, grain N uptake was greater with DCDP than CD, DFDP, and DDFP (Tab. 3). Nitrogen supplied by pea residue likely increased durum and canola grain N uptake, thereby increasing N uptake with DCDP and DDCP, a case similar to that observed for biomass N uptake. Averaged across crop rotations and cultural practices, grain N uptake was greater in 2010 than other years. Above-average growing season precipitation (Fig. 1) may have increased grain N uptake in 2010. Biomass and grain N uptake, however, behaved differently in 2006 and 2010, when growing season precipitation was near or above the average, suggesting that differences in soil water availability due to changes in precipitation among years can vary N uptake between crop biomass and grain.

## 3.2 Soil ammonium-nitrogen

Soil $NH_4$-N content varied with crop rotations at 0–5, 20–50, 50–88, 88–125, and 0–125 cm, with cultural practices at 0–5 cm, and with years at all depths (Tab. 5). Interactions were significant for crop rotation × cultural practice at 0–5 and 50–88 cm, and crop rotation × year, cultural practice × year, and crop rotation × cultural practice × year at 0–5 cm.

At 0–5 cm, $NH_4$-N content was greater with CD than other crop rotations in 2008 and greater with CD and DFDP than DDFP in 2011 in the traditional practice (Fig. 2). In the im-

**Table 4**: Effects of crop rotation and cultural practice on annualized crop biomass (stems and leaves) and grain N uptake from 2005 to 2011.

| Crop rotation[a] | Cultural practice[b] | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| | | Annualized biomass N uptake (kg N $ha^{-1}$)[c] | | | | | | |
| CD | | 32.4a | 113.9a | 19.0c | 49.4a | 41.5b | 92.1a | 51.9ab |
| DCDP | | 41.6a | 103.2a | 110.8a | 72.4a | 70.4a | 84.7a | 49.7b |
| DDCP | | 39.9a | 108.7a | 112.0a | 64.7a | 69.2ab | 74.4a | 52.9ab |
| DFDP | | 40.2a | 92.8a | 61.6b | 54.5a | 60.8ab | 77.3a | 61.6ab |
| DDFP | | 38.5a | 92.4a | 62.3b | 53.1a | 66.9ab | 84.0a | 75.8a |
| | | Annualized grain N uptake (kg N $ha^{-1}$) | | | | | | |
| | Traditional | 60.5a | 37.8a | 55.0a | 54.8a | 60.3a | 66.6b | 51.8b |
| | Improved | 66.2a | 35.1a | 54.3a | 50.2a | 65.4a | 79.5a | 67.0a |

[a] Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

[b] See Tab. 2 for the description of the cultural practice.

[c] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

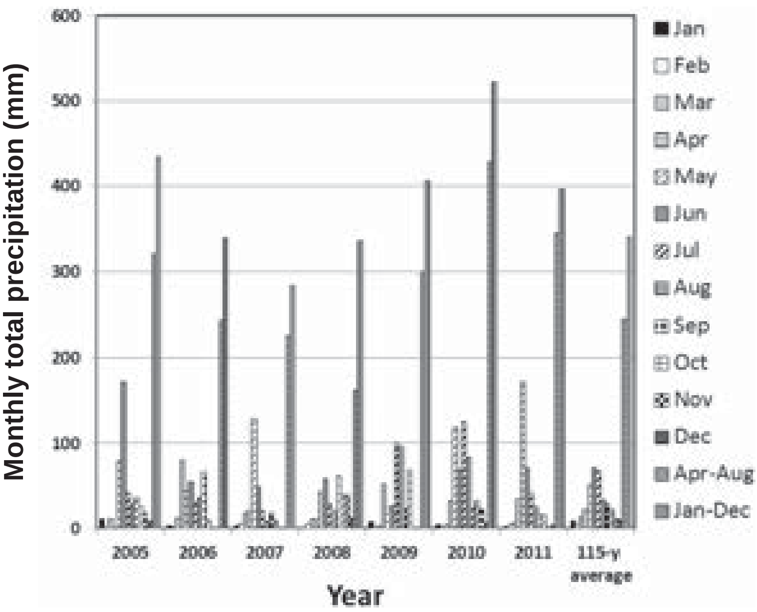

**Figure 1:** Monthly total, crop growing season (April–August), and yearly total (January–December) precipitations from 2005 to 2011 at the experimental site.

proved practice, $NH_4$-N content was greater with CD than DFDP in 2008 and greater with CD, DCDP, and DDFP than DDCP in 2011. Averaged across years, $NH_4$-N content at 0–5 cm was greater with CD than other crop rotations in the traditional practice (Tab. 6). At 50–88 cm, $NH_4$-N content was greater with CD than DDCP and DFDP in the traditional practice and greater with DDCP than DDFP in the improved practice. The $NH_4$-N content at 0–5 cm was also greater in the traditional than the improved practice with CD, DDCP and DFDP, and at 50–88 cm with CD and DDFP.

Higher N fertilization rate to durum than other crops (Tab. 2) likely increased soil residual $NH_4$-N content with CD compared with other crop rotations in traditional and improved cultural practices during below- and above-average growing season precipitation in 2008 and 2011. This is due to the inability of crops to efficiently remove applied N from the soil. Crops can remove ≤ 50% of applied N and their efficiency can be lower at higher N rates (*Varvel* and *Peterson*, 1990; *Eickhout* et al., 2006; *Ross* et al., 2008). Increased soil residual $NH_4$-N content due to greater N fertilization rate with continuous non-legume monocropping than legume–non-legume rotations in the northern Great Plains have been reported by several researchers (*Lenssen* et al., 2007; *Sainju* et al., 2015). Similarly, increased N mineralization from crop residue and soil organic matter due to tillage likely increased $NH_4$-N content at the soil surface in the traditional than the improved practice in some crop rotations (*Sainju* et al., 2012, 2015).

Averaged across cultural practices and years, $NH_4$-N content was greater with CD than other crop rotations at 0–5 cm, greater with CD than DCDP, DDCP, and DDFP at 20–50 cm, greater with CD and DFDP than DDFP at 50–88 cm, and greater with CD, DCDP, DDCP, and DFDP than DDFP at 0–125 cm. While N contribution from pea residue may have resulted in similar $NH_4$-N contents among DCDP, DDCP, and DFDP, lower $NH_4$-N content with DDFP may be related to nature of crops with different N fertilization rates in the cropping sequence in a rotation. Nitrogen fertilization rates were higher for durum and canola, but lower for flax and pea (Tab. 2). Presence of flax and pea with lower N rates in the 3rd and 4th years of the sequence may have re-

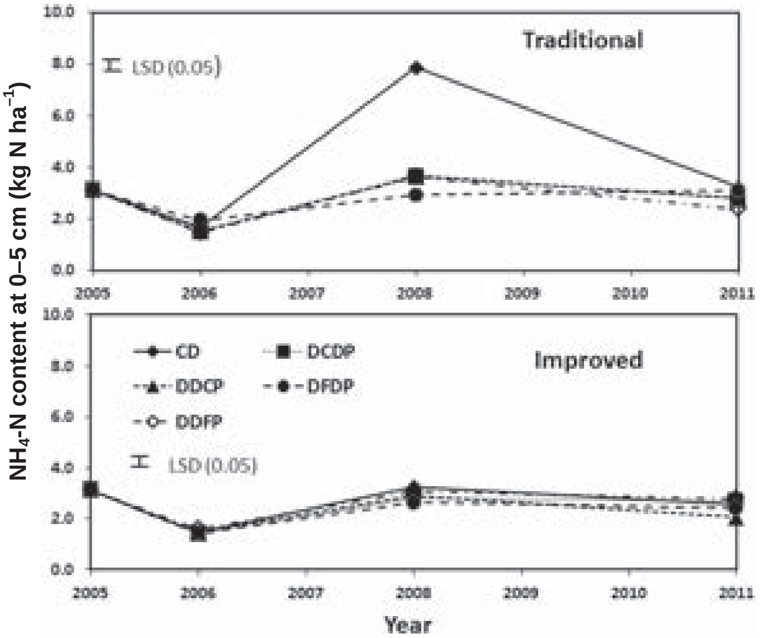

**Figure 2:** Soil $NH_4$-N content at the 0–5 cm depth from 2005 to 2011 as affected by crop rotation and cultural practice (traditional and improved). Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea. See Tab. 2 for the description of the cultural practice. LSD (0.05) is the least significant difference between treatments at $P = 0.05$.

**Table 5**: Soil $NH_4$-N content at various depths as affected by crop rotation and cultural practice averaged across years.

| **Cultural practice**[a] | **Crop rotation**[b] | **$NH_4$-N content at various depths**[c] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **0–5 cm** | **5–10 cm** | **10–20 cm** | **20–50 cm** | **50–88 cm** | **88–125 cm** | **0–125 cm** |
| | | **(kg N ha$^{-1}$)** | | | | | | |
| Traditional | | 3.00a | 2.28a | 3.77a | 8.86a | 11.16a | 13.66a | 43.90a |
| Improved | | 2.51b | 2.31a | 3.81a | 8.80a | 10.49a | 12.16a | 41.24a |
| | CD | 3.29a | 2.47a | 3.87a | 9.55a | 11.39a | 13.35a | 45.20a |
| | DCDP | 2.65b | 2.24a | 3.72a | 8.33c | 10.86ab | 13.18a | 42.43a |
| | DDCP | 2.58b | 2.23a | 3.80a | 8.57bc | 10.69ab | 13.13a | 42.27a |
| | DFDP | 2.59b | 2.29a | 3.84a | 9.17ab | 11.44a | 14.04a | 44.36a |
| | DDFP | 2.65b | 2.24a | 3.71a | 8.52bc | 9.74b | 10.73b | 38.60b |
| Significance | | F values and significance level[d] | | | | | | |
| Crop rotation (R) | | 2.77* | 1.53 | 0.69 | 1.99* | 2.01* | 2.91* | 2.65* |
| Cultural practice (C) | | 18.80* | 0.140 | 0.14 | 0.04 | 1.61 | 1.47 | 1.94 |
| R × C | | 2.43* | 0.37 | 0.77 | 0.30 | 2.96* | 0.84 | 1.52 |
| Year (Y) | | 62.69*** | 192.43*** | 299.98*** | 119.60*** | 204.16*** | 184.18*** | 175.53*** |
| R × Y | | 2.63** | 1.67 | 1.13 | 1.02 | 0.50 | 1.18 | 1.08 |
| C × Y | | 8.00*** | 0.08 | 0.16 | 1.03 | 0.75 | 0.99 | 0.76 |
| R × C × Y | | 1.86* | 0.57 | 0.33 | 0.29 | 0.91 | 0.43 | 0.42 |

[a] See Tab. 2 for the description of the cultural practice.

[b] Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

[c] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

[d] *, **, and *** Significant at $P = 0.05$, 0.01, and 0.001, respectively.

**Table 6**: Soil $NH_4$-N content at 0–5 and 50–88 cm depths as affected by crop rotation and cultural practice averaged across years.

| Crop rotation[a] | Cultural practice at soil depth[bcd] | | | |
|---|---|---|---|---|
| | 0–5 cm | | 50–88 cm | |
| | Traditional | Improved | Traditional | Improved |
| | $NH_4$-N content (kg N $ha^{-1}$) | | | |
| CD | 3.98aA | 2.59aB | 13.17aA | 9.61abB |
| DCDP | 2.78bA | 2.52aA | 10.62abA | 11.09abA |
| DDCP | 2.78bA | 2.39aB | 9.79bA | 11.57aA |
| DFDP | 2.78bA | 2.39aB | 10.58bA | 11.24abA |
| DDFP | 2.66bA | 2.64aA | 11.64abA | 8.91bB |

[a] Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.
[b] See Tab. 2 for the description of the cultural practice.
[c] Numbers followed by different lowercase letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.
[d] Numbers followed by different uppercase letters within a row in a set are significantly different at $P = 0.05$ by the least square means test.

duced $NH_4$-N content in DDFP compared with their alternate-year presence in DFDP where durum with higher N rate in the 3rd year may have maintained $NH_4$-N content.

Averaged across crop rotations and cultural practices, $NH_4$-N content slightly decreased from 2005 to 2006, increased in 2008, and then decreased again in 2011 (Figs. 2 and 3). This trend could be explained by differences in crop grain N uptake due to variations in air temperature and precipitation among years. Although air temperature was similar, grain N uptake was lower in 2007 and 2008 than other years, except 2006, due to reduced crop yield as a result of lower precipitation (Tab. 4, Fig. 1). It may be possible that reduction in grain N uptake due to N inputs from N fertilizers and pea residue may have increased soil $NH_4$-N content in 2008.

### 3.3 Soil nitrate-nitrogen

Soil $NO_3$-N content varied with crop rotations at 5–10, 10–20, 88–125, and 0–125 cm, with cultural practices at 88–125 and 0–125 cm, and with years at all depths (Tab. 7). Significant interactions occurred for crop rotation × year at 5–10, 10–20, 88–125, and 0–125 cm, and for cultural practice × year at all depths, except at 50–88 cm.

At 5–10 cm, $NO_3$-N content, averaged across cultural practices, was greater with CD than all crop rotations in 2006 and 2011, and greater with CD than DCDP and DDCP in 2008 (Fig. 4). At 10–20 cm, $NO_3$-N content was greater with CD, DFDP, and DDFP than DDCP and DCDP in 2008, and greater with CD than DFDP and DDFP in 2011. At 88–125 cm, $NO_3$-N content was greater with CD than DCDP, DDCP, and DDFP in 2008 and greater with DFDP than DDCP in 2011. At 0–125 cm, $NO_3$-N content was greater with CD than DCDP, DDCP, and DDFP in 2008. Averaged across cultural practices and years, $NO_3$-N content was greater with CD than other crop rotations at 5–10 cm, greater with CD, DFDP, and DDFP than DCDP and DDCP at 10–20 cm, and greater with CD than DCDP, DDCP, and DDFP at 88–125 and 0–125 cm (Tab. 7).

Increased soil residual $NO_3$-N content at most soil depths with CD than other crop rotations during years with below- and above-average precipitation was clearly a result of increased N fertilization rate to durum than other crops and lower crop N uptake. Nitrogen fertilization rate was 127 kg N $ha^{-1}$ for durum compared with 6 to 94 kg N $ha^{-1}$ for other crops (Tab. 2). Grain N uptake was also lower with CD than other crop rotations (Tab. 3). This is consistent with various studies (*Varvel* and *Peterson*, 1990; *Riedell* et al., 2009; *Sainju* et al., 2012, 2015) which reported that non-legume monocropping had higher soil residual $NO_3$-N content than legume-based crop rotations due to increased N fertilization rate. Consistently lower $NO_3$-N content with DCDP and DDCP at most soil depths and years suggests that rotating durum with canola and pea can reduce accumulation of residual soil $NO_3$-N content and the potential for N leaching compared with continuous durum. Replacing canola with flax in the crop rotation, however, increased soil $NO_3$-N content because of reduced grain N removal by DFDP and DDFP comparted with DCDP and DDCP (Tab. 3). Grain N removal, across treatments and years, averaged 31 kg N $ha^{-1}$ for flax compared with 37 to 68 kg N $ha^{-1}$ for other crops. No difference, however, was ob-

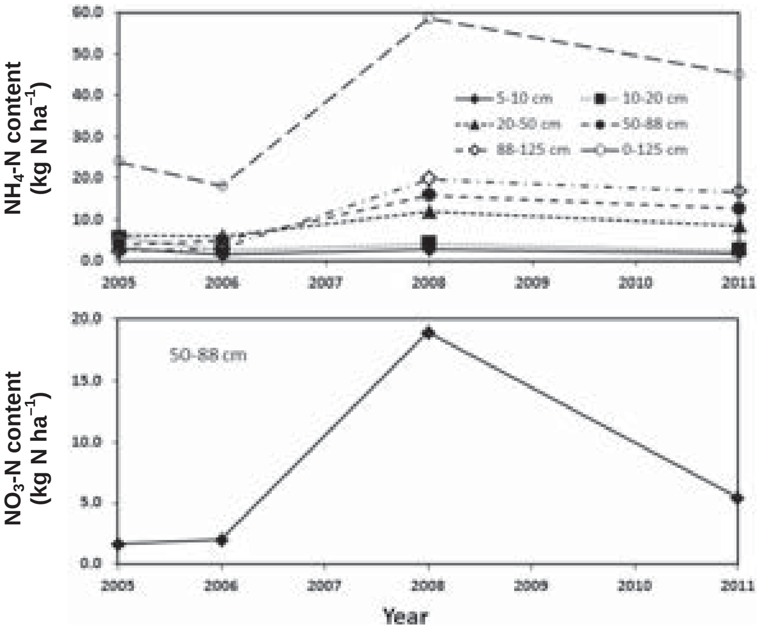

**Figure 3:** Soil $NH_4$-N content at various depths and $NO_3$-N content at the 50–88 cm depth from 2005 to 2011.

**Table 7**: Soil $NO_3$-N content at various depths as affected by crop rotation and cultural practice averaged across years.

| **Cultural practice**[a] | **Crop rotation**[b] | **$NO_3$-N content at various depths**[c] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **0–5 cm** | **5–10 cm** | **10–20 cm** | **20–50 cm** | **50–88 cm** | **88–125 cm** | **0–125 cm** |
| | | **(kg N ha$^{-1}$)** | | | | | | |
| Traditional | | 2.09a | 1.43a | 2.17a | 7.45a | 9.03a | 8.61a | 30.96a |
| Improved | | 1.82a | 1.33a | 2.15a | 6.06a | 8.36a | 6.42b | 26.41b |
| | CD | 2.47a | 1.81a | 2.43a | 8.49a | 9.37a | 9.17a | 33.87a |
| | DCDP | 1.82a | 1.22b | 1.94b | 6.47a | 7.77a | 6.71b | 26.32b |
| | DDCP | 1.86a | 1.19b | 1.93b | 5.97a | 8.07a | 6.38b | 25.59b |
| | DFDP | 1.90a | 1.37b | 2.20a | 6.59a | 9.62a | 8.64ab | 30.60a |
| | DDFP | 1.74a | 1.28b | 2.29a | 6.27a | 8.63a | 6.65b | 27.02b |
| Significance | | F values and significance level[d] | | | | | | |
| Crop rotation (R) | | 1.63 | 4.58** | 1.97* | 1.75 | 1.27 | 3.87** | 3.95** |
| Cultural practice (C) | | 1.38 | 1.45 | 0.04 | 1.06 | 0.81 | 11.28* | 10.13* |
| R × C | | 0.45 | 0.68 | 0.39 | 0.12 | 0.10 | 0.50 | 0.26 |
| Year (Y) | | 61.65*** | 25.53*** | 65.47*** | 39.86*** | 199.78*** | 130.95*** | 408.17*** |
| R × Y | | 1.56 | 2.29** | 3.44*** | 1.66 | 0.83 | 1.96* | 2.43* |
| C × Y | | 3.34* | 3.08* | 4.05** | 6.35** | 0.29 | 3.72* | 3.69* |
| R × C × Y | | 1.15 | 0.91 | 1.09 | 0.18 | 0.21 | 0.90 | 0.46 |

[a] See Tab. 2 for the description of the cultural practice.
[b] Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.
[c] Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.
[d] *, **, and *** Significant at $P = 0.05$, 0.01, and 0.001, respectively.

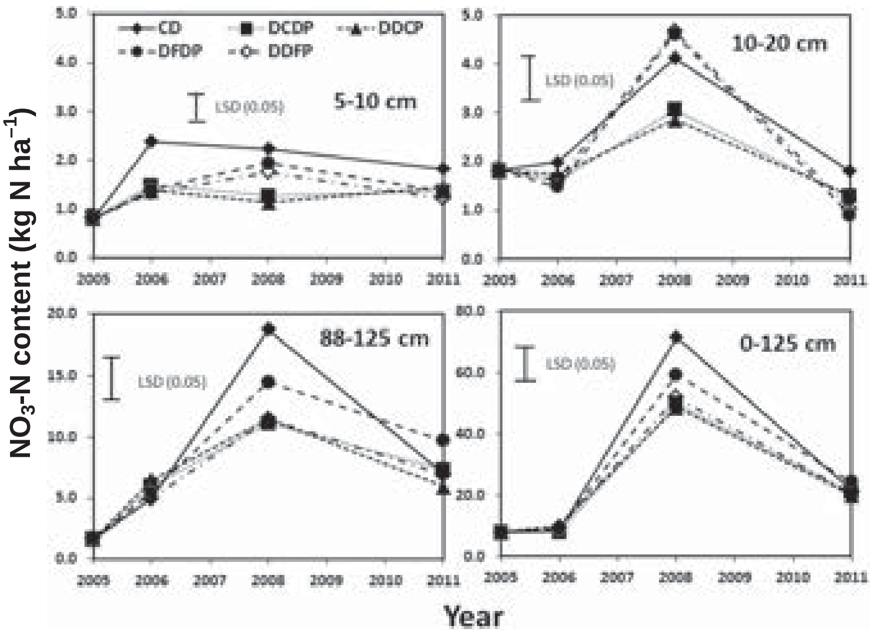

**Figure 4:** Soil $NO_3$-N content at 5–10, 10–20, 88–125, and 0–125 cm depths from 2005 to 2011 as affected by crop rotation. Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea. LSD (0.05) is the least significant difference between treatments at $P = 0.05$.

tained between stacked and alternate-year rotations for soil residual $NO_3$-N content at most depths and years (Tab. 7).

Averaged across crop rotations, $NO_3$-N content was greater with the traditional than the improved cultural practice at 0–5, 5–10, 10–20, 20–50, 88–125, and 0–125 cm in 2008 and at 88–125 cm in 2011 (Fig. 5). Averaged across crop rotations and years, $NO_3$-N content was greater in the traditional than the improved practice at 88–125 and 0–125 cm (Tab. 7). Mineralization of crop residue and soil organic matter due to tillage and reduced grain N uptake due to lower seeding rate and broadcast N fertilization (Tab. 4) likely increased soil residual $NO_3$-N content with the traditional than the improved practice during years with below- and above-average precipitation. Conventional tillage can increase soil residual $NO_3$-N content compared with no-tillage due to increased soil organic matter mineralization (*Soon* et al., 2001; *Al-Kaisi* and *Licht*, 2004; *Sainju* et al., 2015).

Soil $NO_3$-N content increased from 2005 to 2008 and then decreased in 2011 for most soil treatments and depths (Figs. 3 to 5), a trend similar to that observed for $NH_4$-N content. Reduced crop grain N uptake in 2007 and 2008 due to poor crop yield as a result of lower precipitation than in other years (Tabs. 2 and 4) may have increased soil $NO_3$-N content in 2008.

## 3.4 Nitrogen balance

Total N fertilization rate to crops from 2005 to 2011 was greater with CD than other crop rotations, regardless of cultural practices (Tab. 8), as N rate was greater for durum than other crops (Tab. 2). There was no difference in N rates between stacked and alternate-year rotations or between traditional and improved cultural practices. Total N fixed by pea from 2005 to 2011 was greater with DFDP in the improved practice than DDCP and DDFP in the traditional practice and DDCP in the improved practice. There was no N fixation with CD in either traditional or improved practice. Total crop grain N removal from 2005 to 2011 was greater with DCDP in the traditional practice and DCDP, DDCP, and DFDP in the improved practice than CD in the traditional practice. As soil samples from various treatments were composited by depth to a single sample, soil residual N ($NH_4$-N + $NO_3$-N) to a depth of 125 cm at the beginning of the experiment in April 2005 was similar and amounted to 32 kg N $ha^{-1}$ for all treatments. At the end of the experiment in October 2011, soil residual N to a depth of 125 cm was greater with CD, DCDP, and DFDP in the traditional practice than DCDP and DDFP in the improved practice. Nitrogen balance as the difference between N inputs and outputs was greater with stacked and alternate-year crop rotations than CD in both traditional and improved practices.

Crop grain N removal varied from 39% of total N inputs from N fertilizer and pea N fixation with DDFP in the improved practice to 60% with CD in traditional and improved practices. As large part of N supplied by pea residue was unavailable to plants during a growing season, soil residual N remained higher with CD, especially in the traditional practice, due to greater N fertilization rate and N mineralized from crop residue and soil organic matter as a result of tillage. Nitrogen can continue to be mineralized from legume residues for three years, thereby increasing yields of succeeding crops compared with non-legume residues (*Lupwayi* and *Soon*, 2009, 2016). Residual N was also greater with DCDP and DFDP in the traditional practice due to higher N rate applied to durum in the first and third years in alternate-year rotations as opposed to applications in first and second years in the stacked rotations, combined with soil organic N mineralization due to tillage. This suggests that N losses to the environment due to leaching, volatilization, denitrification, surface runoff, and gaseous N emissions can be higher with CD, DCDP, and DFDP in the traditional practice. Because of the slow availability of N from pea residue to succeeding crops, N balance was greater with stacked and alternate-year rotations than CD in both traditional and ecological practices. Most of this N was contributed by pea residue which was immobilized to soil organic N and will be released slowly over years compared with rapid N availability from N fertilizers within a growing season (*Varvel* and *Peterson*, 1990; *Lupwayi* and *Soon*, 2009, 2016). This suggests that legume-based crop rotations can reduce ferti-

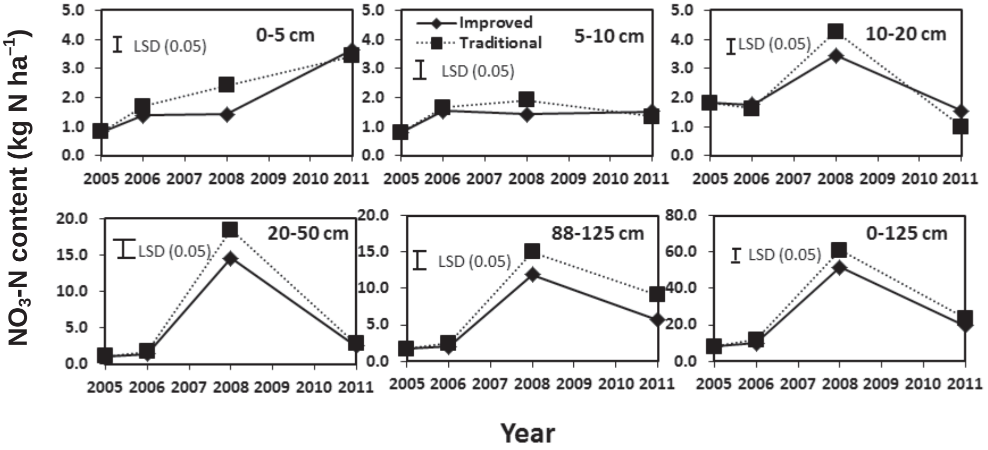

**Figure 5:** Soil $NO_3$-N content at 0–5, 5–10, 10–20, 20–55, 88–125, and 0–125 cm depths from 2005 to 2011 as affected by cultural practice (traditional and improved). See Tab. 2 for the description of the cultural practice. LSD (0.05) is the least significant difference between treatments at $P = 0.05$.

**Table 8**: Nitrogen balance based on total N fertilization to crops, pea N fixation, crop grain N removal from 2005 to 2011, and soil residual N ($NH_4$-N + $NO_3$-N) content in the 0–125 cm depth at the beginning (2005) and end (2011) of the experiment.

| Cultural practice[a] | Crop rotation[b] | Soil residual N in 2005 (A) | Total N fertilization rate (B) | Total pea N fixation (C) | Total grain N removal (D) | Soil residual N in 2011 (E) | N balance[cd] |
|---|---|---|---|---|---|---|---|
| | | (kg N ha$^{-1}$) | | | | | |
| Traditional | CD | 32 | 581a | 0c | 343b | 76a | 194b |
| | DCDP | 32 | 434b | 588ab | 434a | 72a | 548a |
| | DDCP | 32 | 413b | 532b | 399ab | 64ab | 514a |
| | DFDP | 32 | 364b | 560ab | 378ab | 77a | 501a |
| | DDFP | 32 | 378b | 525b | 385ab | 65ab | 492a |
| Improved | CD | 32 | 609a | 0c | 364ab | 63ab | 214b |
| | DCDP | 32 | 420b | 588ab | 455a | 58b | 527a |
| | DDCP | 32 | 441b | 546b | 448a | 65ab | 506a |
| | DFDP | 32 | 385b | 609a | 441a | 66ab | 519a |
| | DDFP | 32 | 392b | 574ab | 378ab | 54b | 566a |

[a] See Tab. 2 for the description of the cultural practice.
[b] Crop rotations are CD, continuous durum; DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–-pea, and DFDP, durum–flax–durum–pea.
[c] N balance = Column (A) + Column (B) + Column (C) – Column (D) – Column (E)
[d] Numbers followed by different letters within a column are significantly different at $P = 0.05$ by the least square means test.

lizer N inputs, decrease N-losses to the environment, especially in the ecological practice, by immobilizing inorganic N to organic forms, and are more productive by increasing crop N uptake compared with non-legume monocropping.

## 4 Conclusions

Soil residual N varied among crop rotations and cultural practices due to differences in N fertilization rates to crops, N supplied by pea residues, N mineralization due to tillage, and crop N uptake. Soil $NH_4$-N content was lower in the improved than the traditional practice at 0–5 cm and lower with DDFP than other crop rotations at 0–125 cm. Soil $NO_3$-N content was also lower in the improved than the traditional practice, but was greater with CD than other crop rotations at most soil depths. Both crop biomass and grain N uptake were lower with CD than other crop rotations and grain N uptake was lower in the traditional than the improved practice during years with above-average precipitation. Nitrogen fertilization rate was greater with CD, but biological N fixation was greater with crop rotations, regardless of cultural practices. Nitrogen balance was greater with stacked and alternate-year rotations than CD in both traditional and improved practices. As a result, legume-based crop rotations can reduce fertilizer N inputs, decrease N losses to the environment, especially in the ecological practice, and can be more productive compared with non-legume monocropping.

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