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Nitrogen balance in dryland agroecosystem in response to tillage, crop rotation, and cultural practice

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Abstract

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Keywords

Cropping system, Management practice, Nitrogen input, Nitrogen output, Nitrogen budget, Soil total nitrogen

Disciplines

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Nitrogen balance in dryland agroecosystem in response to tillage, crop rotation, and cultural practice

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environmentally sustainable by reducing N losses compared with nonlegume monocropping, regardless of cultural practices in dryland agroecosystems.

Keywords Cropping system · Management practice · Nitrogen input · Nitrogen output · Nitrogen budget · Soil total nitrogen

Abbreviations

CT	Conventional tillage
CW	Continuous spring wheat
NT	No-tillage
STN	Soil total N
W–B–C–P	Spring wheat–barley hay–corn–pea
W–B–P	Spring wheat–barley hay–pea
W–P	Spring wheat–pea

Introduction

Crop production must be enhanced with the next generation of green revolution to feed the growing population of 9 billion by 2050 with sustainable intensification (Eickhout et al. 2006; Singh 2013). Application of N fertilizers and manures can increase crop yields; excessive application beyond crops' need, however, not only reduce yields (Smil 1999; Janzen et al. 2003; Eickhout et al. 2006), but also has undesirable consequences on soil and environmental quality, such as soil acidification, N leaching, and emissions of NH_3 and NO_x gases, out of which N_2O is a highly potent greenhouse gas that contributes to global warming (Franzluebbers 2007; Herrero et al. 2010). This is resulted by the inefficient use of N fertilizers by crops, as crops can remove about 40–60% of applied N (Meisinger and Randall 1991; Schepers and Mosier 1991; Wang et al. 2014). Nitrogen-use efficiency of crops can be further reduced at higher N fertilization rates (Varvel and Peterson 1990).

The residual soil N (NO_3-N + NH_4-N) after crop harvest can either be converted to soil organic N or 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 loss to the environment, however, can be reduced by increasing N-use efficiency, enhancing soil N storage, and reducing N fertilization rate using improved management practices, such as crop rotation and cover cropping, compared with traditional practices, such as nonlegume monocropping and no cover cropping (Janzen et al. 2003; Ross et al. 2008; Pieri et al. 2011; Sainju et al. 2012, 2014).

Nitrogen is also added to the soil through dry and wet (snow and rain) depositions from the atmosphere, biological N fixation, and irrigation water. Nitrogen is removed from the agroecosystem through crop grain and biomass harvest. The unharvested N in crop residue (stems and leaves) and roots becomes the core of soil N storage. Accounting of all N inputs and outputs and N retention in the soil yields N balance that can identify dominant processes of N flow and provides a framework to measure agroecosystem performance and environmental sustainability (Watson and Atkinson 1999; Ross et al. 2008).

Recommended N fertilizer rates to crops are usually determined by economical profitability rather than maximum crop yields which vary with soil and climatic conditions, nutrient supply, and competitions with weeds and pests (Schepers and Mosier 1991). As soil residual N and mineralization of crop residue and soil organic matter provide significant N to crops during the growing season, N fertilization rates are usually adjusted by deducting these values so that crop production can be optimized and potential for N losses minimized. Depending on soil temperature and water content, residue addition (fresh or old residue), and soil organic matter, about 1% of soil organic N to a depth of 30 cm in dryland cropping systems to 2% in irrigated cropping systems is mineralized every year (Schepers and Mosier 1991; Wang et al. 2014).

Variations in N inputs, outputs, and retention in the soil can affect N balance among agroecosystems due to differences in soil and climatic conditions, crop species, and management practices (Meisinger and Randall 1991; Ross et al. 2008; Pieri et al. 2011). Nitrogen fertilization rates and losses can be lower in fine- than coarse-textured soils due to increased soil N retention, although predominant N losses are gaseous losses and N leaching in fine-and coarse-textured soils, respectively (Meisinger and Randall 1991; Schepers and Mosier 1991; Wang et al. 2014). Management practices, such as no-till and crop rotation, can result in various N fertilization rates to same or different crops due to differences in soil residual N and N mineralization potential as well as soil N retention and N losses compared with conventional till and monocropping (Ross et al. 2008; Pieri et al. 2011; Sainju et al. 2012, 2014).

Although N balances in agroecosystems have been reported in several long-term experiments (Davis et al. 2003; Ross et al. 2008; Pieri et al. 2011), limited information exists on the effect of management practices on N balance on dryland cropping systems in the northern Great Plains, USA. The reasons for these are the difficulty and complexity of measuring some N inputs and outputs, the need for long-term experiments to reach equilibrium, and increased time, labor, and cost constraints. As a result, some parameters have to be estimated from the literature which add uncertainty to the calculation of N balance values. We examined N flows in the soil–plant–water–air continuum and N balance after 8 years (2004–2011) of tillage, crop rotation, and cultural practice under dryland cropping systems in eastern Montana, USA. Our objectives were to: (1) quantify N flows in crops, soil, and the environment as affected by tillage, crop rotation, and cultural practice, (2) calculate N balance based on N inputs, outputs, and changes in soil N retention, and (3) determine management practices that optimize N balance, reduce N fertilization rate, enhance crop N uptake, and sustain environmental quality. We hypothesized that no-till diversified crop rotation with the improved cultural practice would provide favorable N balance with sustained crop N yield and reduced N rate and N loss to the environment compared with conventional till monocopping with the traditional practice.

Materials and methods

Experimental site and treatments

The experiment was conducted from 2004 to 2011 on a dryland farm, 8 km northwest of Sidney (47°46′N, 104°16′W; elevation 690 m), Montana, USA. Mean monthly air temperature at the site ranges from − 8 °C in January to 23 °C in July and August and mean annual precipitation (105-year average) is 341 mm, 80% of which occurs during the crop growing season (April–October). The soil was a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustolls) which had 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, and 6.1 pH at the 0–20 cm depth. At the initiation of the experiment in April 2004, soil total C and N at 0–20 cm were 27.37 Mg C ha^{-1} and 2.72 Mg N ha^{-1}, respectively. Previous cropping system (10 years) prior to the experiment initiation was spring wheat-fallow under conventional tillage.

Main-plot treatments included two tillage practices (no-tillage [NT] and conventional tillage [CT]) and split-plot treatments were a factorial combination of four crop rotations (continuous spring wheat [CW], spring wheat-pea [W–P], spring wheat–barley hay–pea [W–B–P], and spring wheat–barley hay–corn–pea [W–B–C–P]) and two cultural practices (traditional and improved). Traditional cultural practice included conventional seed rates and plant spacing, conventional planting date, broadcast N fertilization, and reduced spring wheat stubble height and improved cultural practice included variable seed rates and plant spacing, delayed planting, banded N fertilization, and increased spring wheat stubble height. The improved cultural practice has been known to control weeds more effectively than traditional cultural practice (Strydhorst et al. 2008; Nichols et al. 2015). Treatments were arranged in a randomized block design with three replications. The CW was a 1-year rotation with one crop phase (spring wheat); W–P, a 2-year rotation with two phases (spring wheat and pea); W–B–P, 3-year rotation with three phases (spring wheat, barley hay, and pea), and W–B–C–P, a 4-year rotation with four phases (spring wheat, barley hay, corn, and pea). In each rotation, crops were rotated in such a way that every phase of the crop rotation appeared in each year. The sequence of crops in each rotation from 2004 to 2011 is shown in Table 1. Table 2 shows the description of cultural practices used for each crop in the rotation, regardless of tillage and crop rotation. The NT plots were left undisturbed, except for fertilizer application and row crop planting. The CT plots were tilled one to two times a year with a field cultivator to a depth of 7–8 cm for seedbed preparation and weed control. Main plot size was 36.6 × 12.2 m and the split plot 12.2 × 12.2 m.

Crop management and analysis

Every year, P fertilizer as monoammonium phosphate (11% N, 23% P) at 56 kg P ha^{-1} and K fertilizer as muriate of potash (52% K) at 48 kg K ha^{-1} were banded to a depth of 5 cm below and 5 cm away from seeds for all crops at planting in early April to early

Table 1 Description of crops in the rotation employed in all tillage systems and cultural practices from 2004 to 2011

Crop rotation[a]	No. of plot	2004	2005	2006	2007	2008	2009	2010	2011
CW	1	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
W–P	1	Wheat	Pea	Wheat	Pea	Wheat	Pea	Wheat	Pea
	2	Pea	Wheat	Pea	Wheat	Pea	Wheat	Pea	Wheat
W–B–P	1	Wheat	Barley hay	Pea	Wheat	Barley hay	Pea	Wheat	Barley hay
	2	Barley hay	Pea	Wheat	Barley hay	Pea	Wheat	Barley hay	Pea
	3	Pea	Wheat	Barley hay	Pea	Wheat	Barley hay	Pea	Wheat
W–B–C–P	1	Wheat	Barley hay	Corn	Pea	Wheat	Barley hay	Corn	Pea
	2	Barley hay	Corn	Pea	Wheat	Barley hay	Corn	Pea	Wheat
	3	Corn	Pea	Wheat	Barley hay	Corn	Pea	Wheat	Barley hay
	4	Pea	Wheat	Barley hay	Corn	Pea	Wheat	Barley hay	Corn

[a]Crop rotations are CW, continuous spring wheat; W–P, spring wheat–pea; W–B–P, spring wheat–barley hay–pea; and W–B–C–P, spring wheat–barley hay–corn–pea

Table 2 Description of cultural practices (traditional and improved) used for crops in the rotation in all tillage systems and crop rotations

Crop	Cultural practice	Seeding rate (million seeds ha^{-1})	N fertilization at planting	N fertilization rate (kg N ha^{-1})	Planting date	Stubble height (cm)
Spring wheat	Traditional	2.23	Broadcast	101	Early April	20
	Improved	2.98	Banded	101	Early May	30
Pea	Traditional	0.60	Broadcast	6	Early April	5
	Improved	0.92	Banded	6	Early April	5
Barley hay	Traditional	2.23	Broadcast	67	Late April	5
	Improved	2.98	Banded	67	Late April	5
Corn	Traditional	0.04	Broadcast	78	Early May	5
	Improved	0.05	Broadcast	78	Early May	5

May, 2004 to 2011. At the same time, N fertilizer as urea (46% N) and monoammonium phosphate were applied to spring wheat, barley hay, and corn at rates shown in Table 2. A small amount of N fertilizer (6 kg N ha^{-1}) was also applied to pea as monoammonium phosphate was applied as the P fertilizer. Nitrogen fertilization rates to crops were determined by deducting soil NO_3-N content to a depth of 60 cm in the autumn of the previous year from recommended N rates so that excessive N rates can be avoided. As a result, N rates to crops differed in all treatments and years. Nitrogen fertilizer was either broadcast in the traditional cultural practice or banded in the improved practice, except for corn where N fertilizer was broadcast in both cultural practices (Table 2). Immediately after fertilization, spring wheat (cv. Reeder), pea (cv. Majoret), and barley hay (cv. Haybet) were planted at a spacing of 20 cm and corn (cv. 39T67-RR) at 50 cm using a no-till drill during periods as shown in Table 2. Appropriate herbicides and pesticides were applied for each crop at preplanting, during growth, and at postharvest. No irrigation was applied.

Barley hay was harvested by cutting aboveground biomass from an area of 1.5 × 12.0 m with a self-propelled mower-conditioner and round baler after determining biomass yield from two 0.5 m^2 areas outside yield rows on oven-dried (65 °C for 3 days) basis in late June and early July of each year. Total biomass (grains + stems + leaves) yield of spring wheat and pea was determined from two 0.5 m^2 areas per plot as above and grain yield (oven-dried basis) was determined by harvesting grains from a swath of 1.5 × 12.0 m using a combine harvester in August. Corn total biomass and grain yields were determined from areas as described above in October. After grain harvest, biomass residue of spring wheat, pea, and corn were returned to the soil. Biomass residue was left at the soil surface in the no-till system and incorporated into the soil in the conventional till system.

Nitrogen concentration in oven-dried samples of grain and total biomass in spring wheat, pea, and corn and in biomass in barley hay was determined using a high induction furnace C and N analyzer (Elementar, Mt. Laurel, New Jersey, USA) after grinding the samples to 1 mm. Nitrogen content in each component was determined by multiplying N concentration by grain or total biomass yield. Nitrogen content in spring wheat, pea, and corn biomass (stems + leaves), measured as crop residue N returned to the soil, was determined by deducting grain N from total biomass N. Annualized crop residue N or grain N removal for a crop rotation was calculated by dividing the sum of biomass or grain N of all crops by the number of crops in the rotation in a year. Because aboveground biomass was removed for hay and grain yield did not exist in barley, crop residue N returned to the soil and grain N removal for barley hay were considered zero in the calculation of annualized crop residue N returned to the soil and grain N removal in W–B–P and W–B–C–P.

Soil sampling and analysis

After final crop harvest in late October, 2004–2007 and 2011, soil samples were collected from the 0–20 cm depth using a tractor mounted hydraulic probe (3.5 cm inside diameter) after clearing the surface crop residue in all plots. Samples were collected from five places within and between crop rows in the central areas of the plot, composited, placed in the plastic bags in a cooler, transported to the laboratory and weighed. About 10 g soil from each plot was oven-dried at 110 °C for 24 h to determine the dry weight which was used as a conversion factor to determine the dry weight of the entire soil sample. Soil bulk density was determined by dividing the weight of oven-dried soil by the volume of the core. The remainder of the soil was air-dried, ground, and sieved to 2 mm for determining soil total N (STN) concentration.

The STN concentration (g N kg^{-1}) in all soil samples was determined by using a high induction furnace C and N analyzer as above after grinding the samples to < 0.5 mm. The STN content (Mg N ha^{-1}) was calculated by multiplying STN concentration by the bulk density and the thickness of the soil layer using the equivalent soil mass method (Lee et al. 2009). The STN content for a crop rotation was calculated by dividing total STN content under all crops by the number of crops within the rotation in a year. Nitrogen sequestration rate at 0–20 cm was determined by the slope of the line of the linear regression between STN and year.

Nitrogen balance

Total N input (N_{ti}) was calculated as:

$$N_{ti} = N_a + N_b + N_c + N_d + N_e + N_f \quad (1)$$

where N_a = N fertilization rate, N_b = biological N fixation, N_c = soil N mineralization, N_d = atmospheric N deposition, N_e = N added by crop seeds, and N_f = non-symbiotic N fixation. Nitrogen fertilization rate (N_a) for each crop rotation was calculated as mean annualized N rate applied to spring wheat, barley hay, corn, and pea. Biological N fixed by pea (N_b) was calculated as:

$$N_b = 0.7 \times (\text{aboveground pea biomass N} + 0.33 \times \text{total pea aboveground biomass N}) \quad (2)$$

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 × total pea aboveground biomass N refers to estimated belowground biomass N if belowground biomass N is not measured, assuming that belowground biomass N constitutes about one-third of the total aboveground biomass N (Meisinger and Randall 1991). If belowground biomass N is measured, then the estimated value should be replaced by the measured value. Soil N mineralization (N_c) was estimated as 1% of mean STN across years and includes mineralization from both soil organic matter and crop residue (Schepers and Mosier 1991). Atmospheric N deposition (N_d) included wet (rain and snow) and dry (absorption of ammonia and other compounds by the field from the atmosphere) depositions which were each estimated as 7 kg N ha^{-1} $year^{-1}$ (Meisinger and Randall 1991; Ross et al. 2008). Nitrogen added by crop seeds (N_e) in a rotation was determined by averaging N added from seeds of spring wheat, barley hay, corn, and pea in a year. Nitrogen contribution from each crop seed was calculated by multiplying the seed rate by N concentration. Non-symbiotic N fixation (N_f) by blue-green algae and free-living soil bacteria was estimated as 5 kg N ha^{-1} $year^{-1}$ (Stevenson 1982; Ross et al. 2008).

Total N output (N_{to}) was calculated as:

$$N_{to} = N_g + N_h + N_i + N_j + N_k + N_l + N_m \quad (3)$$

where N_g = crop N removal, N_h = ammonia volatilization loss, N_i = denitrification N loss, Nj = N loss during plant senescence, N_k = N leaching loss, N_l = gaseous N (NO, N_2O, and NO_2 emissions) loss, and N_m = N loss from surface runoff. Crop N removal (N_g) for a rotation was determined as the average of N removed in spring wheat, pea, and corn grains and barley hay within the rotation in a year. Nitrogen loss through ammonia volatilization (N_h) was estimated as 15% of applied N fertilizer applied from urea and monoammonium phosphate (Meisinger and Randall 1991; Migliorati et al. 2014). Nitrogen loss through denitrification (N_i) was estimated as 13% of total N input through N fertilizer and atmospheric N deposition after deducting N loss through ammonia volatilization (Meisinger and Randall 1991). Denitrification loss of biologically fixed N was considered negligible (Meisinger and Randall 1991). Nitrogen loss through plant senescence (N_j) was estimated as 5% of the total aboveground biomass N (Meisinger and Randall 1991). Leaching loss of N (N_k) for the semiarid region was estimated as 9 kg N ha^{-1} $year^{-1}$ for continuous spring wheat and 12 kg N ha^{-1} $year^{-1}$ for crop rotations containing legume (pea) (Delgado et al. 2008; Ross et al. 2008). Gaseous N loss (NO, N_2O, and NO_2 emissions) (N_l) was estimated as 1.5% of the applied N fertilizer (IPCC 2014). Nitrogen loss through surface runoff (N_m) was estimated as 1% of the applied N fertilizer (Legg and Meisinger 1982; Ross et al. 2008). All estimated values were obtained from literatures based on medium textured soil (loam and silt loam) in arid and semiarid regions with precipitation < 500 mm similar to our experimental site and with proper management practices (till vs. no-till practices and crop rotation vs. monocropping).

Nitrogen balance was calculated as:

$$\text{Nitrogen balance} = \text{Total N input} - \text{Total N output} - \text{N sequestration rate} \quad (4)$$

A positive value of N balance indicated N surplus and negative value as N deficit in the agroecosystem. This value was used to evaluate the agroecosystem performance and environmental sustainability of treatments due to N flows, retention in the soil, and loss to the environment. Because some parameters were estimated in the calculation of N balance, the uncertainty in N balance was shown as standard error of the mean values.

Statistical analysis of data

Data for annualized crop biomass and grain N, soil bulk density, STN content, N fertilization rate, total N inputs and outputs, and N balance were analyzed using the MIXED procedure of SAS (Littell et al. 2006). Tillage, crop rotation, cultural practice, year and their interactions were considered as fixed effects and replication and tillage × replication as random effects. Linear regression analysis between STN and year was used to calculate N sequestration rate. 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.

Results and discussion

Annualized crop residue nitrogen

Annualized crop residue N returned to the soil varied with crop rotations, cultural practices, and years, with significant interactions for tillage × cultural practice, tillage × year, and crop rotation × year (Table 3). Averaged across tillage and cultural practices, residue N was greater with CW and W–P than W–B–P or W–B–C–P in 2004, 2006, and 2009 and greater with W–P than other crop rotations in 2010 (Table 4). Averaged across crop rotations and years, residue N was greater in the improved than the traditional practice in CT and greater in CT than NT in the improved practice (Table 5). Averaged across crop rotations and cultural practices, residue N was greater in CT than NT in 2010. Averaged across tillage, cultural practices, and years, residue N was greater in CW and W–P than other crop rotations (Table 3). Averaged across treatments, residue N was lower in 2008 than other years.

The greater crop residue N with CW and W–P in most years was due to enhanced growth and N uptake by spring wheat and N fixation by pea in the semiarid dryland cropping systems in the northern Great Plains, USA. Removal of aboveground barley biomass for hay reduced residue N with W–B–P. This, along with poor performance of corn, reduced residue N with W–B–C–P in 2006 and 2010. Higher seeding rate and banded N fertilization increased biomass N uptake and therefore residue N in the improved practice in CT, probably a result of increased N availability. Similarly, increased N availability due to enhanced mineralization of crop residue and soil as a result of tillage may have increased residue N in CT compared with NT. Applied N fertilizer may not be readily available to crops in the NT system due to N immobilization by accumulated crop residue at the soil surface (Bronson et al. 2001; Zibilske et al. 2002). The lower crop residue N in 2008 than other years was due to lower precipitation. Growing season (April–November) precipitation was 185 mm in 2008 compared with 217–397 mm in other years and the 68-year average (Fig. 1).

Annualized crop grain nitrogen removal

Annualized crop grain N removal varied with crop rotations, cultural practices, and years, with a significant interaction for crop rotation × year (Table 3). Averaged across tillage and cultural practices, grain N removal was greater with CW and W–P than W–B–P and W–B–C–P in 2004, 2009, and 2010 (Table 4). In 2006 and 2007, grain N removal was greater with W–P than W–B–P or W–B–C–P. Averaged across tillage, cultural practices, and years, grain N removal was greater with CW and W–P than other crop rotations (Table 3). Averaged across tillage, crop rotations, and years, grain N removal was greater in the traditional than the improved cultural practice. Averaged across treatments, grain N removal was lower in 2008 than other years.

Similar to crop residue N, enhanced grain N uptake by spring wheat and N uptake and/or N fixation by pea increased grain N removal with CW and W–P in 2004, 2009, and 2010. Greater N concentration in pea (25.1 g N kg^{-1}) than spring wheat (15.1 g N kg^{-1}) and corn (12.5 g N kg^{-1}) increased grain N removal with W–P in 2006 and 2007. Removal of aboveground biomass for barley hay and poor performance of corn in the dryland system reduced grain N removal with W–B–P and W–B–C–P in most years. Increased water use due to lower seeding rate and early planting likely increased grain yield and N removal in the traditional cultural practice compared with higher seeding rate and late planting in the improved cultural practice. Lenssen et al. (2014) also reported greater spring wheat grain yield in the traditional cultural practice with lower seeding rate and early planting than the improved cultural practice with higher seeding rate and late planting due to enhanced water uptake. As with crop residue N, lower grain N removal in 2008 than other years was due to reduced precipitation.

Soil bulk density and total nitrogen

Soil bulk density at the 0–20 cm depth varied with tillage systems, with a significant tillage × crop rotation interaction (Table 6). Averaged across cultural practices and years, bulk density was greater in NT with CW and W–B–C–P than CT with CW, W–P, and W–B–P. Averaged across crop rotations, cultural practices, and years, bulk density was greater in NT than CT. Lack of tillage and increased soil compaction appeared to increase bulk density in NT with CW and W–B–C–P.

The STN at 0–20 cm varied with years, with significant interactions for tillage × crop rotation, tillage × year, and tillage × crop rotation × year (Table 6). Averaged across cultural practices, STN was greater in CT with W–B–P than NT with W–P and W–B–P in October 2005 (1.5 years after experiment initiation) (Fig. 2). In October 2007 (3.5 years after experiment initiation), STN was greater in CT with CW than NT with CW. In October 2011 (7.5 years after experiment initiation), STN was greater in NT with W–P than CT with CW, W–P, W–B–P, and W–B–C–P and in NT with W–B–P. Soil N sequestration rates, as obtained by linear regression between STN with year, varied from 29 kg N ha^{-1} year^{-1} in CT with W–P to 89 kg N ha^{-1} year^{-1} in NT with W–P.

Table 3 Annualized crop residue (stems + leaves) N returned to the soil and grain N removal as influenced by crop rotation, cultural practice, and year

Crop rotation[a]	Cultural practice[b]	Year	Crop residue N (kg N ha^{-1})	Grain N removal (kg N ha^{-1})
CW			59a[c]	60a
W–P			66a	65a
W–B–P			43b	45b
W–B–C–P			48b	46b
	Traditional		50	53a
	Improved		52	49b
		2004	60b	58ab
		2005	39d	62ab
		2006	57b	53bc
		2007	49c	62ab
		2008	24e	20d
		2009	59b	70a
		2010	81a	39 cd
		2011	36d	42 cd
Significance				
Tillage (T)			NS	NS
Crop rotation (C)			*	**
T × C			NS	NS
Cultural practice (P)			*	**
T × P			*	NS
C × P			NS	NS
T × C × P			NS	NS
Year (Y)			***	***
T × Y			*	NS
C × Y			*	**
T × C × Y			NS	NS
P × Y			NS	NS
T × P × Y			NS	NS
C × P × Y			NS	NS
T × C × P × Y			NS	NS

NS not significant

[a]Crop rotations are CW, continuous wheat; W–P, spring wheat–pea; W–B–P, spring wheat–barley hay–pea; and W–B–C–P, spring wheat–barley hay–corn–pea

[b]See Table 2 for the description of 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

*Significant at $P = 0.05$

**Significant at $P = 0.01$

***Significant at $P = 0.001$

Averaged across cultural practices and years, STN was greater in CT with W–P and NT with CW and W–B–C–P than CT with CW and NT with W–B–P (Table 6).

The greater STN in CT with W–P and NT with CW and W–B–C–P were likely to be the results of increased N inputs from N fertilizer and N returned

Table 4 Interaction between crop rotation and year on annualized crop residue (stems + leaves) N returned to the soil and grain N removal

Crop rotation[a]	Crop residue N (kg N ha^{-1})							
	2004	2005	2006	2007	2008	2009	2010	2011
CW	79a[b]	40	79a	52	21	74a	81b	45
W–P	74a	51	74a	64	27	74a	112a	50
W–B–P	43b	30	50b	44	20	49b	73b	32
W–B–C–P	61ab	41	50b	44	26	58ab	72b	31
	Grain N removal (kg N ha^{-1})							
	2004	2005	2006	2007	2008	2009	2010	2011
CW	87a	67	54ab	68ab	12	80a	57a	53
W–P	76a	72	67a	86a	24	97a	65a	45
W–B–P	48b	57	47b	57b	23	53b	30b	39
W–B–C–P	47b	57	50ab	53b	18	42b	27b	38

[a]Crop rotations are CW, continuous wheat; W–P, spring wheat–pea; W–B–P, spring wheat–barley hay–pea; and W–B–C–P, spring wheat–barley hay–corn–pea

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

Table 5 Interactions between tillage, cultural practice, and year on annualized crop residue (stems + leaves) N returned to the soil

Cultural practice[a]	Year	Crop residue N (kg N ha^{-1})	
		Tillage	
		Conventional tillage (CT)	No-tillage (NT)
Traditional		49b[b]	50
Improved		56aA[c]	49B
	2004	61b	58b
	2005	38d	40c
	2006	52bc	59b
	2007	50c	47c
	2008	23e	26d
	2009	60b	59b
	2010	89aA	74aB
	2011	37d	35 cd

[a]See Table 2 for the description of cultural practice

[b]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

[c]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

to the soil from crop residue. Nitrogen fertilization rates were greater with CW than other crop rotations (Table 7). Although N fixed by pea was greater in W–P, W–B–P, and W–B–C–P (Table 8), N returned to the soil from crop residue was greater with CW and W–P than W–B–P and W–B–C–P (Table 3). Increased STN with greater N inputs returned to the soil from N fertilization and crop residue were known (Eck and

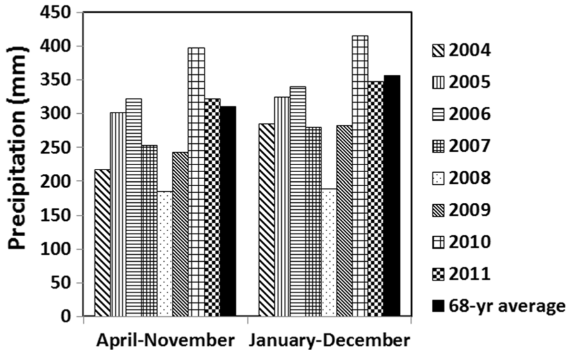

Fig. 1 Crop growing season (April–November) and annual (January–December) precipitation from 2004 to 2011 at the experimental site

Jones 1992; Sherrod et al. 2003; Sainju et al. 2007). Removal of aboveground biomass for barley hay reduced N input and decreased STN with W–B–P, especially in the NT system. The greater STN in NT with CW and W–B–C–P were also probably due to reduced mineralization of crop residue and soil organic N due to undisturbed soil condition as a result of no-tillage. Increased STN in NT compared with CT under dryland cropping systems in the northern Great Plains, USA were reported by several researchers (Sainju et al. 2007; Engel et al. 2017). As a result, soil N sequestration rate was higher in NT with W–P than other treatments (Fig. 2).

Nitrogen inputs

The amount of N fertilizer applied to crops was greater with CW than other crop rotations in all tillage systems and cultural practices (Tables 7, 9, 10), because N requirement was higher for spring wheat than other crops (Table 2). In contrast, lower N requirements for other crops, followed by N fixed by pea residues (Table 8), reduced the amount of N fertilizer in other crop rotations. Because of reduced crop growth and N uptake (Tables 3, 4) as a result of lower growing season and annual precipitation (Fig. 1), soil NO_3-N

Table 6 Interaction between tillage and crop rotation on soil bulk density and total N (STN) at the 0–20 cm depth

Tillage[a]	Crop rotation[b]	Bulk density (Mg m^{-3})	STN (Mg ha^{-1})
CT	CW	1.28b[c]	3.19b
	W–P	1.27b	3.38a
	W–B–P	1.31b	3.32ab
	W–B–C–P	1.33ab	3.26ab
NT	CW	1.39a	3.36a
	W–P	1.35ab	3.28ab
	W–B–P	1.36ab	3.20b
	W–B–C–P	1.39a	3.37a
Significance			
Tillage (T)		*	NS
Crop rotation (C)		NS	NS
T × C		*	**
Cultural practice (P)		NS	NS
T × P		NS	NS
C × P		NS	NS
T × C × P		NS	NS
Year (Y)		NS	***
T × Y		NS	**
C × Y		NS	NS
T × C × Y		NS	*
P × Y		NS	NS
T × P × Y		NS	NS
C × P × Y		NS	NS
T × C × P × Y		NS	NS

NS not significant

[a]Tillage are CT, conventional tillage; and NT, no-tillage

[b]Crop rotations are CW, continuous wheat; W–P, spring wheat–pea; W–B–P, spring wheat–barley hay–pea; and W–B–C–P, spring wheat–barley hay–corn–pea

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

*Significant at $P = 0.05$

**Significant at $P = 0.01$

***Significant at $P = 0.001$

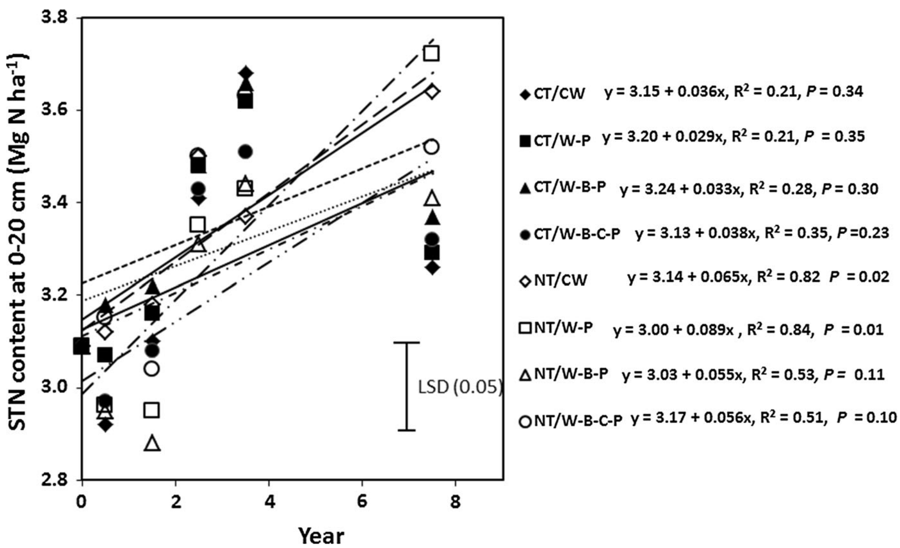

Fig. 2 Relationship between soil total N (STN) at the 0–20 cm depth and year. CT/CW represents conventional tillage with spring wheat; CT/W–P, conventional tillage with spring wheat–pea; CT/W–B–P, conventional tillage with spring wheat–barley hay–pea; CT/W–B–C–P, conventional tillage with spring wheat–barley hay–corn–pea; NT/CW, no-tillage with spring wheat; NT/W–P, no-tillage with spring wheat–pea; NT/W–B–P, no-tillage with spring wheat–barley hay–pea; and NT/W–B–C–P, no-tillage with spring wheat–barley hay–corn–pea. Solid and dotted lines represent regression lines of STN versus year for various treatments. Year 0, 0.5, 1.5, 2.5, 3.5, and 7.5 represents time of soil sampling in April 2004, October 2004, October 2005, October 2006, October 2007, and October 2011, respectively. LSD (0.05) is the least significant differences in STN between treatments in a year at $P = 0.05$

content was higher in 2008 in all treatments, which resulted in lower N rates to all crops in all treatments in 2009, 2010, and 2011 (Table 7).

Nitrogen fixed biologically by pea in aboveground biomass also varied with treatments and years (Table 8). Absence of pea resulted in no biological N fixation with CW. Pea N fixation was lower in 2008 than other years due to poor pea growth as a result of reduced precipitation (Fig. 1). Nitrogen fixation, however, was greater in 2009 and 2010 than other years due to enhanced pea growth as a result of above-average precipitation. Averaged across years, pea N fixation was greater in NT with W–B–C–P than other tillage and crop rotations in the traditional cultural practice (Table 9). In the improved cultural practice, pea N fixation was similar among W–P, W–B–P, and W–B–C–P, but was greater than CW in both CT and NT (Table 10).

Estimated soil N mineralization was similar in all treatments (Tables 9, 10). Estimated N inputs from atmospheric N deposition and nonsymbiotic N fixation were minor and also similar in all treatments. Estimated N added from crop seeds was also minor and was slightly lower with W–B–C–P than other crop rotations due to lower N concentration in corn than spring wheat, barley, and pea. Total N input was 14–27% greater in W–P, W–B–P, and W–B–C–P than CW in CT and NT in traditional and improved cultural practices (Tables 9, 10). Greater estimated pea N fixation in above- and belowground biomass increased total N inputs in these treatments.

Nitrogen outputs

Crop grain N removal was greater in NT with W–B–P and W–B–C–P than CT with CW and NT with W–P in the traditional cultural practice (Table 9). In the improved cultural practice, N removal was greater in CT and NT with W–B–P and NT with W–B–C–P than CT with CW. Greater N removal by barley hay increased N removal with W–B–P and W–B–C–P in all tillage systems and cultural practices. Estimated N losses through ammonia volatilization and denitrification were greater with CW than other crop rotations in all tillage systems and cultural practices due to increased N fertilization rate (Tables 7, 9, 10). Increased N rate can increase N losses through ammonia volatilization and denitrification (Meisinger and Randall 1991, Ross et al. 2008; Pieri et al. 2011).

Table 7 Amount of N fertilizer applied to various treatments from 2004 to 2011

Cultural practice[a]	Tillage[b]	Crop rotation[c]	N fertilizer applied (kg N ha^{-1})							
			2004	2005	2006	2007	2008	2009	2010	2011
Traditional	CT	CW	101	101	101	101	101	20	42	74
		W–P	34	67	34	67	34	21	10	29
		W–B–P	42	67	59	42	67	16	13	35
		W–B–C–P	49	69	63	65	49	18	23	36
	NT	CW	101	101	101	101	101	20	37	74
		W–P	56	51	51	51	51	21	24	26
		W–B–P	51	56	56	56	56	16	30	27
		W–B–C–P	62	62	62	62	62	22	26	38
Improved	CT	CW	101	101	101	101	101	21	32	66
		W–P	101	67	101	67	101	22	20	35
		W–B–P	84	34	51	84	33	17	35	19
		W–B–C–P	82	48	60	56	82	2	15	27
	NT	CW	101	101	101	101	101	21	47	74
		W–P	56	51	51	51	51	17	16	22
		W–B–P	51	56	51	56	56	19	25	27
		W–B–C–P	62	62	56	62	62	19	23	30
LSD (0.05)[d]			52	53	62	56	52	19	27	28

[a] See Table 2 for the description of cultural practice

[b] Tillage are CT, conventional tillage; and NT, no-tillage

[c] Crop rotations are CW, continuous wheat; W–P, spring wheat–pea; W–B–P, spring wheat–barley hay–pea; and W–B–C–P, spring wheat–barley hay–corn–pea

[d] Least significant difference between treatments at $P = 0.05$

Estimated N loss through plant senescence, which depends on total crop aboveground biomass N (Meisinger and Randall 1991, Ross et al. 2008), was similar among crop rotations in all tillage systems and cultural practices. Estimated N loss through leaching from applied N fertilizer and biological N fixation (Ross et al. 2008; Pieri et al. 2011; IPCC 2014; Migliorati et al. 2014) was lower with CW than other crop rotations, because of the absence of biological N fixation in this treatment. Estimated N losses through gaseous (NO, N_2O, and NO_2) emissions and surface runoff, that also occur both from applied N fertilizer and biological N fixation (Ross et al. 2008; Pieri et al. 2011; IPCC 2014; Migliorati et al. 2014), were minor in all treatments. Total N output was not affected by treatments and ranged from 90 to 114 kg N ha^{-1} $year^{-1}$.

Nitrogen balance

Change in N level as obtained by the difference between total N input and output was greater in NT with W–P and W–B–C–P than CT with CW and NT with CW and W–B–P in the traditional cultural practice (Table 9). In the improved cultural practice, change in N level was greater in CT with W–P than CT and NT with CW and W–B–P (Table 10). Increased N fixation by pea increased change in N level in CT and NT with W–P and W–B–C–P in both cultural practices. Lack of biological N fixation reduced change in N level with CW, although N fertilization rate was greater in this treatment. This suggests that biological N fixed by legumes constitutes an important source of N input while calculating the N balance, a result similar to those reported by various researchers (Poudel et al. 2001; Ross et al. 2008; Pieri et al. 2011; Sainju et al. 2016). Increased crop N removal in

Table 8 Biological N fixed by pea in various treatments from 2004 to 2011

Cultural practice[a]	Tillage[b]	Crop rotation[c]	Biological N fixed by pea (kg N ha^{-1})							
			2004	2005	2006	2007	2008	2009	2010	2011
Traditional	CT	CW	0	0	0	0	0	0	0	0
		W–P	61	40	65	76	38	95	97	49
		W–B–P	54	50	61	81	31	92	93	43
		W–B–C–P	67	42	80	80	37	118	43	48
	NT	CW	0	0	0	0	0	0	0	0
		W–P	65	61	73	70	35	105	78	40
		W–B–P	31	49	71	79	37	77	82	60
		W–B–C–P	73	75	85	80	51	128	57	67
Improved	CT	CW	0	0	0	0	0	0	0	0
		W–P	66	37	70	70	41	96	51	58
		W–B–P	64	52	67	80	32	97	103	62
		W–B–C–P	64	47	72	89	45	101	46	62
	NT	CW	0	0	0	0	0	0	0	0
		W–P	50	69	52	90	40	86	76	58
		W–B–P	55	63	73	63	43	84	64	53
		W–B–C–P	65	55	91	93	33	102	49	51
LSD (0.05)[d]			25	30	23	24	10	25	30	NS[e]

[a]See Table 2 for the description of cultural practice

[b]Tillage are CT, conventional tillage; and NT, no-tillage

[c]Crop rotations are CW, continuous wheat; W–P, spring wheat–pea; W–B–P, spring wheat–barley hay–pea; and W–B–C–P, spring wheat–barley hay–corn–pea

[d]Least significant difference between treatments at $P = 0.05$

[e]Not significant

grain and hay reduced change in N level with W–B–P in all tillage systems and cultural practices.

Nitrogen balance as calculated by the difference between change in N level and N sequestration rate at 0–20 cm was greater in CT with W–P, W–B–P, and W–B–C–P than other treatments, except in NT with W–B–C–P, in the traditional cultural practice (Table 9). In the improved cultural practice, N balance was greater in CT with W–P and W–B–C–P than other tillage and crop rotations, except in CT with W–B–P (Table 10). Greater change in N level and lower N sequestration rate increased N balance in CT with W–P and W–B–C–P in both traditional and improved cultural practices. The reverse was true for lower N balance in NT with CW and W–P in both cultural practices. Unaccounted N varied from − 39 kg N ha^{-1} $year^{-1}$ in NT with CW in the traditional practice to 41 kg N ha^{-1} $year^{-1}$ in CT with W–P in the improved practice. Negative N balance show N loss (deficit), but positive balance represents N gain (surplus). The uncertainty in N balance values ranged from 10% in CT with W–P in the traditional practice to 33% in NT with W–B–P and W–B–C–P in the improved practice.

Nitrogen balance values close to zero suggest that the flow of N through N inputs, outputs, and retention in the soil can be robustly accounted in an agroecosystem (Ross et al. 2008; Pieri et al. 2011; Sainju et al. 2016). This was especially true in CT with CW and NT with W–B–P and W–B–C–P in both traditional and improved cultural practices in our experiment. In these practices, it is likely that N was effectively recycled in the soil–plant–environment continuum. In CW, increased N losses through volatilization, denitrification, leaching, surface runoff, and gaseous emissions compared with other crop rotations resulted in N deficit, except in CT with CW in the traditional practice. Nitrogen deficit also

Table 9 Annual N balance due to difference between total N input and output and N sequestration rate from 2004 to 2011 in the traditional cultural practice

Parameter	N balance in the traditional practice (kg N ha^{-1} $year^{-1}$)							
	Conventional tillage (CT)				No tillage (NT)			
	CW[a]	W–P[a]	W–B–P[a]	W–B–C–P[a]	CW	W–P	W–B–P	W–B–C–P
N inputs								
N fertilization rate	78A[b]	37B	43B	47B	80A	40B	44B	49B
Pea N fixation	0C	65B	67B	62B	0C	64B	60B	76A
Soil N mineralization	32	34	33	33	34	33	32	34
Atmospheric N deposition	14	14	14	14	14	14	14	14
N added by crop seed	3	3	3	2	3	3	3	2
Non-symbiotic N fixation	5	5	5	5	5	5	5	5
Total N input	132C	158B	165AB	163AB	136C	159AB	158B	180A
N outputs								
Crop N removal	63B	68AB	74AB	72AB	68AB	62B	80A	79A
Denitrification	10	6	7	7	11	6	7	7
Ammonia volatilization	12	6	6	7	12	6	7	7
Plant senescence	6	6	6	6	6	7	6	7
N leaching	9	12	12	12	9	12	12	12
Gaseous N (NO_x) emissions	1	1	1	1	2	1	1	1
Surface runoff	1	1	0	1	2	1	1	1
Total N output	102	100	106	106	110	95	114	114
Change in N level[c]	30C	58AB	59AB	57AB	26C	64A	44B	66A
N sequestration rate (0–20 cm)[d]	36	29	33	38	65	89	55	56
N balance[e]	− 6 (± 1)B	29 (± 3)A	26 (± 3)A	19 (± 4)A	− 39 (± 5)C	− 25 (± 7)BC	− 11 (± 2)B	10 (± 2)AB

[a]Crop rotations are CW, continuous spring wheat; W–P, spring wheat–pea; W–B–P, spring wheat–hay barley–pea, and W–B–C–P, spring wheat–hay barley–corn–pea

[b]Numbers followed by different letters within a row are significantly different at $P = 0.05$ by the least square means test

[c]Change in N level = Total N input − total N output

[d]Determined from the linear regression analysis between soil total N (STN) at 0–20 cm and year from 2004 to 2011

[e]N balance = Change in N level − N sequestration rate (0–20 cm). Values are mean (± SD)

occurred in NT with W–P and W–B–P in both cultural practices due to increased N sequestration rate and crop N removal. Although N losses to the environment through various processes were accounted for while calculating the N balance, difficulties in measuring them have led us to estimate their values from the literature which add uncertainty to N balance values. The uncertainty in estimated N inputs and outputs can range from 5% in atmospheric N deposition to as much 50% in N losses through ammonia volatilization, denitrification, and N leaching (Sainju 2017). Nitrogen balance values were lower in NT than CT in both cultural practices, probably a result of increased soil N retention, as N sequestration rates were higher in NT than CT for all crop rotations. Similar results of lower N balance in NT than CT have been reported for dryland cropping systems (Sainju et al. 2009). The values were, however, similar between traditional and improved cultural practices, a case similar to that observed by Sainju et al. (2016).

Our N balance values of − 39 to 41 kg N ha^{-1} $year^{-1}$ for various management practices were similar

Table 10 Annual N balance due to difference between total N input and output and N sequestration rate from 2004 to 2011 in the improved cultural practice

Parameter	N balance in the improved practice (kg N ha^{-1} $year^{-1}$)							
	Conventional tillage (CT)				No tillage (NT)			
	CW[a]	W–P[a]	W–B–P[a]	W–B–C–P[a]	CW	W–P	W–B–P	W–B–C–P
N inputs								
N fertilization rate	78A[a]	40B	45B	47B	81A	38B	44B	47B
Pea N fixation	0B	72A	62A	69A	0B	65A	62A	67A
Soil N mineralization	32	34	33	33	34	33	32	34
Atmospheric N deposition	14	14	14	14	14	14	14	14
N added by crop seed	3	3	3	2	3	3	3	2
Non-symbiotic N fixation	5	5	5	5	5	5	5	5
Total N input	132B	168A	162A	170A	137B	158A	160A	169A
N outputs								
Crop N removal	50B	66A	79A	71AB	57AB	64AB	79A	76A
Denitrification	10	6	7	7	11	6	7	7
Ammonia volatilization	12	6	6	7	12	6	7	7
Plant senescence	6	7	7	7	6	6	6	6
N leaching	9	12	12	12	9	12	12	12
Gaseous N (NO_x) emissions	2	1	1	1	1	0	0	1
Surface runoff	1	0	0	1	1	0	0	1
Total N output	90	98	112	106	97	94	111	110
Change in N level[c]	42C	70A	50BC	64AB	40C	64AB	49BC	59AB
N sequestration rate (0–20 cm)[d]	36	29	33	38	65	89	55	56
N balance[e]	6 (± 1)B	41 (± 6)A	17 (± 3)AB	26 (± 5)A	− 25 (± 3)C	− 25 (± 4)C	− 6 (± 2)BC	3 (± 1)B

[a]Crop rotations are CW, continuous spring wheat; W–P, spring wheat–pea; W–B–P, spring wheat–hay barley–pea, and W–B–C–P, spring wheat–hay barley–corn–pea

[b]Numbers followed by different letters within a row are significantly different at $P = 0.05$ by the least square means test

[c]Change in N level = Total N input − total N output

[d]Determined from the linear regression analysis between soil total N (STN) at 0–20 cm and year from 2004 to 2011

[e]N balance = Change in N levels − N sequestration rate (0–20 cm). Values are mean (± SD)

to or greater than the reported values of − 39 to 13 kg N ha^{-1} $year^{-1}$ for various cropping systems in US, Canada, and Europe (Drinkwater et al. 1998; Poudel et al. 2001; Davis et al. 2003; Ross et al. 2008; Pieri et al. 2011; Sainju et al. 2016). Most of the reported N balance values were for various cropping systems and crop rotations under CT systems and few were reported for NT systems. Several researchers (Korsaeth and Eltun 2000; Karrison et al. 2003) have reported N balances of − 45 to 45 kg N ha^{-1} $year^{-1}$ for several long-term cropping systems, suggesting that crop production occurred at the expense of STN and that STN values were highly variable among cropping systems to be used for calculating N balance.

Out of the total N input added to crops, crop N removal accounted for 42–50% with CW and 39–45% with other crop rotations containing pea in all tillage systems and cultural practices. In contrast, estimated total N loss to the environment ranged from 29 to 31% of the total N input with CW and 19–22% with other crop rotations. This suggests that legume-based crop rotations can reduce N losses to the environment compared with nonlegume monocropping, although crop N removal was similar with all crop rotations, regardless of tillage systems and cultural practices. Our values for crop N removal were similar to the values of 39–48% of the total N input reported for dryland cropping systems (Ross et al. 2008; Davis et al. 2003; Sainju et al. 2016), but values for N loss to the environment were within 6–33% reported for various cropping systems by numerous researchers (Paustian et al. 1990; Crews and Peoples 2005; Ross et al. 2008). Differences in soil and climatic conditions, cropping systems, management practices, and duration of the experiment may have influenced the proportion of crop N removal and N loss to total N input among regions.

Conclusions

Nitrogen balance based on N inputs, outputs, and retention in the soil showed a complete picture on N flows in crops and soils and losses to the environment after 8 years of tillage, crop rotation, and cultural practices in the northern Great Plains, USA. Crop residue N returned to the soil was greater with CW and W–P, but N removal in grain and hay was greater with W–B–P and W–B–C–P than other crop rotations. Nitrogen fertilization rate was greater with CW, but biological N fixation was greater with other crop rotations. Soil N sequestration rate at 0–20 cm from 2004 to 2011 was greater in NT with W–P than other tillage and crop rotations. Total N input was lower, but the proportion N loss to environment as total N input was greater with CW than other crop rotations, regardless of tillage and cultural practices. As a result, N flows through crop, soil, and the environment were more accountable in legume-based crop rotations, especially in CT systems. Increased soil N sequestration increased N deficit in NT systems which partly contrasted our hypothesis. Legume-based crop rotations can reduce N inputs, increase aboveground crop N removal and N flows, and decrease N loss to the environment compared with nonlegume monocropping, regardless of tillage and cultural practices. As a result, legume-based crop rotations can be productive and environmentally sustainable with reduced chemical inputs compared with nonlegume monocropping in dryland agroecosystems.

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