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Improving Dryland Cropping System Nitrogen Balance with No-Tillage and Nitrogen Fertilization

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Abstract: Studies on N balance due to N inputs and outputs and soil N retention to measure cropping system performance and environmental sustainability are limited due to the complexity of measurements of some parameters. We measured N balance based on N inputs and outputs and soil N retention under dryland agroecosystem affected by cropping system and N fertilization from 2007 to 2011 in the northern Great Plains, USA. Cropping systems were conventional tillage barley (*Hordeum vulgaris* L.)-fallow (CTB-F), no-tillage barley-fallow (NTB-F), no-tillage barley-pea (*Pisum sativum* L.) (NTB-P), and no-tillage continuous barley (NTCB). Nitrogen rates to barley were 0, 40, 80, and 120 kg N ha^{-1}. Total N input due to N fertilization, pea N fixation, soil N mineralization, atmospheric N deposition, nonsymbiotic N fixation, and crop seed N and total N output due to grain N removal, denitrification,

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volatilization, N leaching, gaseous N (NO_x) emissions, surface runoff, and plant senescence were 28 to 37% greater with NTB-P and NTCB than CTB-F and NTB-F. Total N input and output also increased with increased N rate. Nitrogen sequestration rate at 0 to 10 cm averaged 22 kg N ha^{-1} yr^{-1} for all treatments. Nitrogen deficit ranged from 5 to 16 kg N ha^{-1} yr^{-1}, with greater deficits for CTB-F and NTB-P and higher N rates. Because of increased grain N removal and reduced N loss to the environment and N fertilizer requirement, NTB-P with 40 kg N ha^{-1} can enhance agronomic performance and environmental sustainability while reducing N inputs compared to other management practices.

Keywords: Dryland cropping system**;** Management practices**;** Nitrogen budget; Nitrogen input; Nitrogen output.

Abbreviations: CTB-F, conventional tillage barley-fallow; NTB-F, no-tillage barley-fallow; NTB-P, no-tillage barley-pea; and NTCB, no-tillage continuous barley.

1. Introduction

Nitrogen fertilization is one of the most important management practices to increase crop yields from the limited land so that food supply can be enhanced to feed nine billion people by 2050 [1, 2]. As N is a major nutrient, crops require N in large amount to sustain yields compared to other nutrients [1, 3]. However, N application beyond crops' need not only reduces yields [1, 3, 4], but also degrades soil and environmental quality by increasing soil acidification, N

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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 [5, 6]. As crops can remove about 40 to 60% of applied N [7, 8, 9], the residual N (NO_3-N + NH_4-N) accumulated in the soil profile after crop harvest can either be conserved as soil organic N or lost to the environment through leaching, denitrification, surface runoff, soil erosion, volatilization, and N_2O emissions [1, 3, 4, 10]. Nitrogen use by crops is further reduced at higher N rates [11]. Improved management practices, such as no-tillage, crop rotation, and cover cropping has potential to increase cropping system N-use efficiency, improve environmental quality, and reduce N loss compared with traditional practices, such as nonlegume monocropping, crop-fallow rotation, and no cover cropping [3, 10, 12, 13, 14].

Besides N fertilization, other sources of N inputs include dry and wet (snow and rain) depositions from the atmosphere, biological N fixation, soil N mineralization, irrigation water, nonsymbiotic N fixation, and crop seeds [3, 10, 12]. Nitrogen outputs include N removal through crop grain and biomass harvest and N loss through various processes as mentioned above. The unharvested N in crop residue (stems and leaves) and roots contribute to soil N storage. Some of the applied N through manures and fertilizers can also convert into soil organic N. Nitrogen balance based on N inputs, outputs, and soil N storage can identify dominant processes of N flows and provide a framework to measure a cropping system performance and agroecosystem sustainability [10, 15].

Nitrogen fertilization rates to crops to maximize economic profitability vary with soil and climatic conditions and how efficiently nutrient cycles within the agroecosystem [8]. Therefore, fertilizer application rates are usually determined by estimating soil residual N at planting and N mineralization during the crop-growing season from recommended N rates so that crop production and N-use efficiency are maximized and the potential for N losses minimized. As it is

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not possible to determine soil N mineralization at crop planting due to the long time required for determination, it is estimated that about 1% to 2% of soil organic N is mineralized every year, depending on soil temperature, soil water content, crop residue addition, and soil organic matter content [8, 9].

Agroecosystem N balance can be affected by variations in N inputs, outputs, and retention in the soil under diverse soil and climates, crop species, and management practices [7, 10, 12]. Studies on N balance in agroecosystems under various cropping systems have been reported in some long-term experiments [10, 12, 16]. Despite a vast area of dryland cropping systems in the northern Great Plains of USA, limited information is available concerning the effect of management practices on dryland agroecosystem N balance. Difficulties and complexity of measuring some N inputs and outputs, high variability in yield responses to N inputs associated with interannual climate variability, the need of long-term experiments to reach equilibrium, and thereby increased time, labor, and cost constraints have resulted on limited studies on N balance. These constrain also increases uncertainty to the calculation of N balance values in dryland cropping systems. Several researchers [10, 17] have reported that legume-based cropping systems have N surplus due to legume N fixation and lower N loss to the environment compared to nonlegume monocropping. Others [18] found that tillage and cultural practice did not affect dryland agroecosystem N balance.

A study was designed to estimate N flows in the soil-plant-water-air system and N balance from 2007 to 2011 under dryland cropping systems in eastern Montana, USA under diverse cropping system and N fertilization rates. The main objectives of this study were to: (1) evaluate N flows in crops, soil, and the environment under diverse cropping systems and N fertilization rates, (2) quantify N balance based on N inputs, outputs, and N sequestration rate, and (3)

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determine management practices that reduce N fertilization rate, enhance crop N uptake, and improve environmental quality. We hypothesized that no-tillage legume-nonlegume crop rotation with reduced N rate would provide favorable N balance by enhancing crop N removal, reducing external N inputs and N loss to the environment, and increasing soil N retention compared to conventional tillage crop-fallow with increased N rate.

2. Materials and Methods

2.1. Study Site and Treatments

The study was conducted from 2006 to 2011 at a farm site, 11 km west of Sidney (48° 33'N, 104° 50'W), eastern Montana, USA. The study site has a mean monthly air temperature of -8°C in January to 23°C in July and August and mean annual precipitation (68-yr average) of 357 mm, 70% of which occurs during the crop-growing season (April-August). The soil is classified as a Williams loam (fine-loamy, mixed, superactive, frigid, Typic Argiustolls), with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, and 7.2 pH at the 0- to 10-cm depth in samples collected in October 2006. Soil organic C and total N contents at 0 to 10 cm were 18.8 Mg C ha^{-1} and 1.86 Mg N ha^{-1}, respectively. The study site was under conventional tillage with spring wheat-fallow rotation for ten-years cropping system before the establishment of the experiment.

The study had a randomized complete block split-plot arrangement of treatments and three replications. Main-plot treatments were four cropping systems (no-tillage continuous barley [NTCB], no-tillage barley-pea [NTB-P], no-tillage barley-fallow [NTB-F], and conventional tillage barley-fallow [CTB-F]). Each main plot was divided into four subplots where one of the four N fertilization rates (0, 40, 80, and 120 kg N ha^{-1}) as the split-plot treatment was applied to

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barley, but not to pea and fallow. Each main-plot treatment had two cropping phases (e.g., two barley phases in NTCB, barley and pea phases in NTB-P, and barley and fallow phases in NTB-F and CTB-F) which were present in every year. The CTB-F with 80 kg N ha^{-1} represents a typical dryland farming practice for barley in the region. No-tillage plots were not disturbed, except for fertilizer application and planting crops in rows using a no-till drill. In CTB-F, a field cultivator equipped with C-shanks and 45-cm wide sweeps and coiled-toothed spring harrows with 60 cm rods were used to till the plots to a depth of 10 cm at planting and during fallow periods two to three times a year for seedbed preparation and weed control. Weeds in no-tillage plots were controlled by applying preplant and postharvest herbicides while in conventional tillage plots by a combination of herbicides and tillage to a depth of 10 cm as needed. The plot size for the main-plot treatment including two crop phases was 48.0 m × 12.0 m and the split-plot treatment was 12.0 × 12.0 m.

2.2. Crop Management and Soil Sampling

In April 2007 to 2011, six-row barley (cv. Certified Tradition) was planted at 45 kg ha^{-1}, and pea (cv. Majoret) inoculated with proper *Rhizobium sp.* at 101 kg ha^{-1} to a depth of 3.8 cm using a no-till drill equipped with double-shoot Barton disk openers. At planting, P fertilizer as triple super phosphate (45% P) at 29 kg P ha^{-1} and K fertilizer as muriate of potash (52% K) at 27 kg K ha^{-1} were banded to barley and pea at 5 cm to the side and below the seeds, but not to fallow. Nitrogen fertilizer as urea (46% N) to barley was broadcast to meet N rates of 0, 40, 80, or 120 kg N ha^{-1} a week after planting. These N rates were adjusted for soil NO_3-N content to a depth of 60 cm after crop harvest in the autumn of the previous year to avoid excessive levels of residual soil N after crop harvest. Irrigation was not applied to all the treatments. Two days before grain harvest in August 2007 to 2011, barley and pea biomass (stems + leaves) were harvested from

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two 0.5 m^2 areas outside yield rows, ears or pods were separated from biomass, and oven-dried at 60ºC for 3 d, and weighed to estimate the aboveground biomass. Biomass samples were ground to 1 mm for N analysis. Barley and pea grain yields were determined on an oven-dried basis from an 11.0 × 1.5 m swath using a combine harvester after oven-drying subsamples at 60ºC for 3 d and adjusting for dry matter yield. The subsamples were ground to 1 mm for N analysis. After grain harvest, barley and pea residues were returned to the soil.

In October 2006 to 2011, soil samples were collected with a hand probe (2.5 cm inside diameter) to a depth of 10 cm from five places in central rows of each plot and composited. Because changes in soil total N occur only at 0 to 10 cm where tillage is employed for seed bed preparation and weed control under dryland cropping systems at the site after five years [13], it was decided to collect soil samples only from this depth to determine total N content. A subsample was oven dried at 110º C to determine the dry weight, from which the bulk density was determined by dividing the weight of the oven-dried soil by the volume of the core. The remainder of the soil samples was air dried, ground, and sieved to 2 mm for analysis of total N concentration.

2.3. Laboratory Analysis

Total N concentration (g N kg^{-1}) in crop grain and biomass was analyzed using a high combustion C and N analyzer (LECO Corp., St Joseph, MI). Nitrogen removal in grain and crop residue N (kg N ha^{-1}) returned to the soil were calculated by multiplying grain and biomass yields by their N concentrations. Total aboveground biomass N was calculated as the sum of grain N removal and crop residue N. Annualized crop residue N or grain N removal for a cropping sequence was calculated by dividing the sum of residue or grain N of all crops by the

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number of crops in the rotation in a year. Because crops were absent during the fallow phase, crop residue N and grain N removal in fallow phases for NTB-F and CTB-F were considered zero.

Soil total N concentration (g N kg^{-1}) was determined by using the C and N analyzer as above after grinding the soil samples to <0.5 mm. Soil total N content (Mg N ha^{-1}) was calculated by multiplying total N concentration by the bulk density and the soil layer thickness. Soil total N content for a cropping sequence was calculated by averaging the total N contents in all cropping phases within a rotation.

2.4. 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. Biological N fixed by pea (N_b) was calculated as:

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

Where, 0.7 is the conversion factor for N fixed by pea, assuming that legumes fix 70% of N and takes up 30% from the soil [7, 10, 12]. When belowground biomass N is not measured, the value 0.33 × total aboveground pea biomass N refers to the estimated belowground biomass N, assuming that belowground biomass N constitutes about one-third of the total aboveground biomass N [7]. Because we measured total aboveground biomass N of pea, but not belowground biomass N, we calculated belowground biomass N and pea N fixation using equation (2).

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Including N mineralization from both soil organic matter and crop residue, N mineralization (N_c) was estimated as 1% of soil total N content for all treatments under dryland cropping systems [8]. Atmospheric N deposition (N_d) included both wet (rain and snow) and dry (absorption of ammonia and other compounds by the field from the atmosphere) depositions, and each was estimated as 7 kg N ha^{-1} yr^{-1} [7, 10]. Nitrogen added by crop seeds (N_e) in a rotation was determined by averaging N added from seeds of all crops in a year. For the fallow phase, N added by crop seed was considered zero. Nitrogen contribution from each crop seed was calculated by multiplying the seeding 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} yr^{-1} [10, 19].

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 grain N removal, N_h = N loss through ammonia volatilization, N_i = denitrification N loss, Nj = N loss during plant senescence, N_k = N leaching loss, N_l = N loss through gas (NO, N_2O, and NO_2) emissions, and N_m = N loss through surface runoff. Nitrogen loss through ammonia volatilization (N_h) was estimated as 15% of N applied from urea and monoammonium phosphate [7, 20]. Nitrogen loss through denitrification (N_i) was estimated as 13% of total N input from N fertilizer and atmospheric N deposition after deducting N loss through ammonia volatilization [7, 21]. In the calculation of this parameter, denitrification loss of biologically fixed N was considered negligible [7]. Nitrogen loss through plant senescence (N_j) was estimated as 5% of total aboveground biomass N [7, 21]. Nitrogen loss through leaching (N_k) for the semiarid region was estimated as 9 kg N ha^{-1} yr^{-1} for barley and 12 kg N ha^{-1} yr^{-1} for pea [10, 22]. Gaseous N loss (NO, N_2O, and NO_2 emissions) (N_l) was estimated as 1.5% of the

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applied N fertilizer [23]. Nitrogen loss through surface runoff (N_m) was estimated as 1% of the applied N fertilizer [10, 24]. All estimated N values were obtained from literature based on medium textured soil (loam and silt loam) in semiarid regions with precipitation <500 mm similar to our experimental site and management practices (tillage vs. no-tillage practices and crop rotation vs. monocropping and fallow).

Nitrogen balance was calculated as:

Nitrogen balance = Total N input – Total N output – N sequestration rate [4]

Because the regression analysis of soil total N with a year for all treatments was not significant, N sequestration rate (kg N ha^{-1} yr^{-1}) was calculated by deducting soil total N content in 2006 from that in 2011 and divided by the number of years. Change in N level was calculated by deducting the total N output from total N input. A positive value of N balance indicated N surplus and a negative value indicated N deficit in the agroecosystem. This value was used to evaluate the cropping system performance and environmental sustainability as affected by treatments.

2.5. Data Analysis

Data for annualized crop residue N and grain N removal, soil bulk density and total N content, N fertilization rate, total N input and output, change in N level, and N balance were analyzed using the MIXED procedure of SAS [25]. Cropping system was considered as the main-plot factor and N fertilization rate as the split-plot factor for data analysis. Fixed effects were a cropping system, N rate, and their interactions; random effects were replication and cropping system × replication, and repeated measure variable was year. Linear regression analysis between soil total N content and year was conducted to calculate N sequestration rate.

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The least square means test was performed to separate means when treatments and interactions were significant [25]. Statistical significance was evaluated at $P \leq 0.05$ unless otherwise stated.

3. Results and Discussion

3.1. Annualized Crop Residue Nitrogen

Annualized crop residue N returned to the soil varied among cropping systems, N fertilization rates, and years, with a significant interaction for cropping system × year (Table 1). Averaged across N rates, residue N was greater with NTB-P and NTCB than CTB-F and NTB-F in 2007 and 2008 and greater with NTB-P than other cropping sequences from 2009 to 2011 (Table 2). The absence of crops during the fallow period reduced residue N with CTB-F and NTB-F in all years. In contrast, greater biomass yield of barley and higher N concentration in pea than barley increased residue N with NTB-P compared with NTCB from 2009 to 2011 when the growing season precipitation was near or above the average. Growing season precipitation was 292 to 349 mm from 2009 to 2011 compared to the 68-yr average of 311 mm. During the below-average precipitation in 2007 and 2008, lower biomass yield in pea than barley resulted in similar residue N between NTB-P and NTCB. Nondifference in residue N between CTB-F and NTB-F in all years suggests that tillage had no influence in crop residue N. Several researchers [13, 26] have also observed that tillage did not affect crop residue N returned to the soil under dryland cropping systems in the northern Great Plains.

Residue N, averaged across cropping systems and years, increased linearly with increased N rate (Fig. 1). As soil N availability increases with N fertilization, it is not surprising to observe

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greater residue N with increased N rates [27, 28]. Differences in crop residue N returned to the soil among treatments are expected to influence soil total N as discussed below.

3.2. Soil Bulk Density and Total Nitrogen

Soil bulk density at the 0- to 10-cm depth was not affected by treatments and years and averaged 1.44 (± 0.01) Mg m^{-3} (Table 3). Cultivation of soil to a shallow depth (10 cm) in conventional tillage treatments did not affect the bulk density compared to no-tillage treatments. Differences in cropping systems and N rates among treatments also did not affect bulk density. Similarly, cropping system, N rate, and their interaction did not affect soil total N at 0 to 10 cm (Table 3). Soil total N, averaged across treatments, varied among years, with greater levels from 2007 to 2009 than other years. Increased crop residue N returned to the soil (Table 2) increased soil total N from 2007 to 2009. Increased soil total N with greater N inputs from crop residue and N fertilization were known [17, 29, 30]. For determining N sequestration rate, linear regression analysis of soil total N with year indicated that the regression equation was not significant. Therefore, N sequestration rate calculated as the difference in soil total N at 0 to 10 cm between 2011 and 2006 divided by the number of years averaged 22 kg N ha^{-1} yr^{-1} for all treatments.

3.3. Nitrogen Inputs

The annualized amount of N fertilizer applied to barley varied among cropping systems, N rates, and years, with significant interactions for cropping system × year and N rate × year (Table 1). The amount of N fertilizer, averaged across N rates, was greater with NTCB than other cropping systems in all years, except in 2008 and 2009 (Table 4). Application of N fertilizer to barley in both cropping phases increased the amount of N fertilizer with NTCB compared with CTB-F, NTB-F, and NTB-P where no N fertilizer was applied during the fallow and pea phases.

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Greater soil residual NO_3-N in 2007 resulted in lower amount of N fertilizer applied for all treatments in 2008.

The amount of N fertilizer, averaged across cropping systems, increased with increased N rate in all years (Table 4). Differences in soil residual NO_3-N content among N rates and years resulted in different amount of N fertilizer. Biological N fixed by pea in NTB-P also varied among years, with lower fixation in 2008 than other years. Lower precipitation reduced pea growth and N fixation in 2008. The absence of legumes resulted in no biological N fixation with CTB-F, NTB-F, and NTCB. In contrast, biological N fixation averaged across cropping systems and years, was small (4.2 to 5.3 kg N ha^{-1} yr^{-1}) with N rate treatments (Table 4). Because of nonsignificant differences in soil total N among treatments, estimated soil N mineralization was not significantly different between treatments and ranged from 18.4 to 20.5 kg N ha^{-1} yr^{-1} (Figs. 2 and 3). Estimated N inputs from atmospheric N deposition and nonsymbiotic N fixation were also similar in all treatments. Nitrogen added from crop seeds was minor.

Total N input varied among cropping systems, N rates, and years, with significant interactions for cropping system × year and N rate × year (Table 5). Although the interactions of cropping system and N rate with year were significant, discussion on the effect of only main treatments on total N input was considered for simplicity, because their trends among years were similar. This resulted in similar conclusions, thereby eliminating the need for displaying a large number of data. Total N input was greater with NTB-P and NTCB than CTB-F and NTB-F (Fig. 4) and linearly increased with increased N rate (Fig. 5). Nitrogen inputs from biological N fixation and N fertilizer with NTB-P and N fertilizer applied to both phases of barley with NTCB increased total N input with these cropping sequences. Similarly, a greater amount of N fertilizer applied to barley increased total N input, as N rate increased.

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3.4. Nitrogen Outputs

Annualized crop grain N removal varied among cropping systems, N fertilization rates, and years, with a significant cropping system × year interaction (Table 1). Averaged across N rates, grain N removal was greater with NTB-P and NTCB than CTB-F and NTB-F in 2007, 2009, and 2010, but was greater with CTB-F than NTCB in 2008 (Table 2). The absence of crops during the fallow period reduced grain N removal with CTB-F and NTB-F in 2007, 2009, and 2010 when the growing season precipitation (April-August) was near or above the average. In contrast, greater grain yield and higher N concentration in pea than barley increased grain N removal with NTB-P compared with NTCB in 2010 when the growing season precipitation was above the average. During the below-average precipitation in 2008, however, greater grain N removal with CTB-F than NTCB was due to increased grain yield probably a result of enhanced soil water conservation during the fallow period. Such increases in soil water conservation during the fallow period and annualized crop grain yield and N uptake with crop-fallow compared with continuous cropping during dry years with below-average precipitation have been reported by various researchers [13, 26, 31]. Nondifference in grain N removal between CTB-F and NTB-F in all years suggests that tillage did not influence grain N removal. Several researchers [13, 26] have also observed that tillage had no effect on crop yield and N uptake in dryland cropping systems in the northern Great Plains.

Grain N removal, averaged across cropping systems and years, linearly increased with increased N rate (Fig. 1). As soil N availability increases with N fertilization, it is not surprising to observe higher crop grain N removal with increased N rates [26, 28]. As grain N removal was not different between 80 and 120 kg N ha^{-1}, application of 120 kg N ha^{-1} to dryland barley is

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probably excessive and should be discouraged to reduce the cost of N fertilization, the potential for N leaching, and N_2O emissions.

Estimated N losses through ammonia volatilization and denitrification were greater with NTCB than other cropping systems and increased with increased N rate (Figs. 6 and 7). Greater amount of N fertilizer applied to continuous barley with NTCB and increased N rate enhanced N losses through these processes in these treatments. Increased N rate can enhance N losses through ammonia volatilization and denitrification [7, 10, 12]. Estimated N loss through plant senescence was greater with NTB-P and NTCB than other cropping systems and increased with increased N rate. This was due to greater total crop aboveground biomass N in these treatments (Table 2, Fig. 2), as increased crop N content can enhance N loss through plant senescence [7, 10]. Because of greater total N input, estimated N loss through leaching was greater with NTB-P than other cropping systems and increased with increased N rate. Increased N input can enhance N leaching [10, 12, 20, 23]. Estimated N losses through gaseous (NO, N_2O, and NO_2) emissions and surface runoff due to applied N fertilizer and biological N fixation [10, 12, 20, 23] were minor in all treatments.

Total N output varied among cropping systems, N rates, and years, with a significant cropping system × year interaction (Table 5). As with total N input, only the effect of main treatments on total N output was discussed, because similar trends of cropping system and N rate among years occurred. Total N output was greater with NTB-P and NTCB than CTB-F and NTB-F (Fig. 4) and increased linearly with increased N rate (Fig. 5). Greater grain N removal increased total N output with NTB-P and NTCB. Similarly, greater grain N removal, followed by increased N losses through denitrification, ammonia volatilization, plant senescence, N leaching, gaseous emissions, and surface runoff increased total N output, as N rate increased.

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3.5. Nitrogen Balance

Change in N level, as calculated by the difference between total N input and output, varied among N rates and years, with significant interactions for cropping system × year and N rate × year (Table 5). Change in N level was greater with NTB-F and NTCB than NTB-P (Fig. 4) and increased curvilinearly with increased N rate (Fig. 5). Greater total N input than output increased changed in N level with NTB-F and NTCB greater with 120 and 80 than 0 and 40 kg N ha^{-1}. In contrast, nondifference in total N output due to similar grain N removal resulted in a similar change in N level between 0 and 40 kg N ha^{-1}.

Nitrogen balance varied among cropping systems, N rates, and years, with significant interactions for cropping system × year and N rate × year (Table 5). Although the interactions of cropping system and N rate with year were significant for N balance, display of such data for each year resulted in five additional tables with similar conclusions. Therefore, as with total N input and output, only data for N balance affected by cropping system and N rate averaged across years were shown for simplicity and meaningful discussion. All treatments showed N deficit (Figs. 4 and 5). Nitrogen deficit was greater with CTB-F and NTB-P than NTB-F and curvilinearly increased with increased N rate. Lower change in N level increased N deficit with these treatments. Unaccounted N in the N balance varied from -4.7 kg N ha^{-1} yr^{-1} with 120 kg N ha^{-1} to 15.7 kg N ha^{-1} yr^{-1} with NTB-P. The uncertainty in N balance values ranged from 32% with NTB-F to 53% with 120 kg N ha^{-1}.

The flow of N through N inputs, outputs, and storage in the soil can be robustly accounted in an agroecosystem when N balance values approach to zero [10, 12, 17]. This was especially true in the120 kg N ha^{-1} treatment. It is likely that N was effectively recycled in the soil-plant-

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environment continuum in this treatment. Similar N sequestration rates have led to small differences in N balance among treatments. Ross et al. [10] also reported nonsignificant differences in N sequestration rates among various cropping systems and N fertilizer sources even after 25 yr in western Canada. Although we accounted for all N losses to the environment through various processes for calculating the N balance, difficulties and complexities in measuring them have led us to estimate their values from the literature, which added uncertainty to N balance calculation. Studies show that the uncertainty in estimated N inputs and outputs can range from as less as 5% in atmospheric N deposition to as much 50% in N losses through ammonia volatilization, denitrification, and leaching [7, 21]. As a result, our uncertainty in N balance values of 32 to 53% was similar to 30 to 53% reported by Ross et al. [10] in western Canada but greater than 10 to 33% reported by Sainju et al. [18] in eastern Montana.

Greater N deficit with CTB-F than NTB-F suggests that conventional tillage can increase the deficit compared with no-tillage. Although we estimated N mineralization based on soil total N (Table 5), tillage can increase N mineralization by disrupting soil aggregates and increasing aeration and microbial activity compared with no-tillage. This can increase soil residual N and therefore N loss to the environment through various processes which can increase N deficit. A similar result of greater N deficit with conventional tillage compared with no-tillage has been reported for dryland cropping systems [17]. Similarly, greater N deficit with NTB-P than NTCB suggests that legume-nonlegume rotation can increase the deficit compared with continuous nonlegume. This is in contrast to those reported by several researchers [10, 17] who reported that legume-based crop rotations could increase N surplus compared with continuous nonlegume monocropping. However, variations in N deficits among treatments are small and need further

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verification by conducting long-term experiments where differences in N sequestration rates among treatments can be measured.

The N balance values of -16 to -5 kg N ha^{-1} yr^{-1} for diverse management practices were lower than the reported values of -39 to 13 kg N ha^{-1} yr^{-1} for various cropping systems in US, Canada, and Europe [10, 12, 16, 17, 32, 33]. Most of the reported N balance values were for cropping systems under conventional tillage management while few were reported under no-tillage systems. Nitrogen balance values of as much as -45 to 45 kg N ha^{-1} yr^{-1} for several long-term cropping systems have been reported by other researchers [34, 35] who suggested that most of the N cycling under crop production occurred at the expense of soil total N which was highly variable among treatments and years.

Out of the total N input, crop grain N removal accounted for 54, 49, 63, and 54% with CTB-F, NTB-F, NTB-P, and NTCB, respectively. Similarly, grain N removal accounted for 66, 64, 54, and 48% of the total N input with 0, 40, 80, and 120 kg N ha^{-1}, respectively. In contrast, estimated total N loss to the environment through various processes were 32, 31, 29, and 31% of the total N input with CTB-F, NTB-F, NTB-P, and NTCB, respectively. Consequent values were 15, 24, 30, and 33% of the total N input with 0, 40, 80, and 120 kg N ha^{-1}, respectively. This suggests that NTB-P removed more N from the soil through grain production while reducing N loss to the environment compared with other cropping systems. In contrast, grain N removal decreased while N loss to the environment increased, as N rate to barley increased. As grain N removal was greater with NTB-P than CTB-F and NTB-F and there was no difference in grain N removal between 40 and 80 kg N ha^{-1} while reducing N fertilization rate and N loss to the environment, NTB-P with 40 kg N ha^{-1} can be recommended as a novel management practice to

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enhance dryland agroecosystem performance and environmental sustainability and reduce external N inputs for crop production.

Our crop grain N removal values were similar to or greater than the values of 39 to 48% of the total N input reported for dryland cropping systems [10, 16, 17], but values for N loss to the environment were within 6-33% reported for diverse cropping systems [10, 36, 37]. Differences in soil and climatic conditions, cropping systems, management practices, and duration of a study could influence the proportion of crop N removal and N loss to total N input among regions.

4. Conclusions

This study demonstrated N flows in crops and soils and losses to the environment for calculating N balance based on N inputs, outputs, and storage in the soil after five years of tillage, cropping system, and N fertilization rate in the northern Great Plains, USA. The amount of N fertilizer applied to barley was greater with NTCB than other cropping systems and increased with increased N rate. Nitrogen removed by crop grain was greater with NTB-P and NTCB than CTB-F and NTB-F and also increased with increased N rate. As a result, total N input and output were also greater with NTB-P and NTCB than other cropping systems and greater with increased N rate. Soil N sequestration rate at 0 to 10 cm was not affected by treatments. Nitrogen deficit was slightly greater with NTB-P than NTB-F and NTCB and greater with lower N rates. The proportion of grain N removal to the total N input was greater, while the proportion of total N loss was lower in NTB-P than other cropping systems. Similarly, the proportion of grain N removal to the total N input increased, but the proportion of N loss to the environment decreased, as N rate increased. As a result, NTB-P with 40 kg N ha^{-1} can be a

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robust management practice to sustain agronomic performance and environmental quality while reducing N fertilization rate in dryland cropping systems, although the practice slightly increased N deficit.

Author Contributions: U.M. Sainju designed the experiment, analyzed data, and wrote the manuscript; R. Ghimire and G P. Pradhan contributed in data analysis, writing, and revision of the manuscript.

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Table 1. Analysis of variance for crop grain N removal and residue N content and the amount of N fertilizer applied to barley with sources for cropping system, N fertilization rate, year, and their interactions.

Source	Grain N removal	Residue N content	Amount of N fertilizer applied
Cropping system (C)	**	***	**
N fertilization rate (N)	***	**	***
C × N	NS	NS	NS
Year (Y)	***	***	***
C × Y	***	*	*
N × Y	NS	NS	***
C × N × Y	NS	NS	NS

*Significant at $P \leq 0.05$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$; NS, not significant.

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Table 2. Annualized crop grain N removal and residue N content from 2007 to 2011 as affected by cropping system.

Cropping system [a]	2007	2008	2009	2010	2011	Mean
	----------(kg N ha^{-1})----------					
	Grain N removal					
CTB-F	26.3b [b]	29.7a	36.2b	26.7c	26.9	29.2b
NTB-F	25.0b	24.9ab	35.8b	25.7c	26.1	27.5b
NTB-P	63.4a	16.3ab	70.2a	64.7a	30.0	49.5a
NTCB	51.1a	14.0b	58.8a	51.0b	36.0	42.2a
	Residue N content					
CTB-F	10.3b	17.1b	7.3bc	9.7b	9.1b	8.9c
NTB-F	8.8b	16.5b	6.3c	5.6b	5.4b	7.1c
NTB-P	19.0a	25.5a	18.9a	20.6a	21.5a	17.6a
NTCB	21.5a	25.2a	12.9b	10.8b	10.1b	13.4b

[a] Cropping systems are CTB-F, conventional tillage barley-fallow; NTB-F, no-tillage barley-fallow; NTB-P, no-tillage barley-pea; and NTCB, no-tillage continuous barley.

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

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Table 3. Soil bulk density and total N content at the 0- to 10-cm depth from 2006 to 2011 averaged across cropping systems and N fertilization rates.

Year	Bulk density (Mg m^{-3})	Total N (Mg N ha^{-1})
2006	1.42	1.86b[a]
2007	1.43	2.08a
2008	1.45	2.13a
2009	1.45	2.11a
2010	1.44	1.94b
2011	1.43	1.99b
N sequestration rate (kg N ha^{-1} yr^{-1})		22.0
Significance		
Cropping system (C)	NS	NS
N fertilization rate (N)	NS	NS
C × N	NS	NS
Year (Y)	NS	***
C × Y	NS	NS
N × Y	NS	NS
C × N × Y	NS	NS

***Significant at $P \leq 0.001$; NS, not significant.

[a] Numbers followed by different letters in a column are significantly different at $P \leq 0.05$ by the least square means test.

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Table 4. Annualized amount of N fertilizer applied to barley as affected by cropping system and N fertilization rate and biological N fixed by pea in no-till barley-pea rotation.

Cropping system [a]	N fertilization rate	2007	2008	2009	2010	2011	Mean	Mean pea N fixation with N rate
		----------(kg N ha^{-1})----------						
CTB-F		30.0b [b]	0.3	15.6b	6.0b	21.3b	14.6b	
NTB-F		30.0b	4.5	21.3ab	7.5b	19.6b	16.6b	
NTB-P		30.0b	0.3	17.3b	16.5b	18.9b	16.6b	
NTCB		60.0a	3.8	30.8a	35.0a	46.0a	35.1a	
Pea N fixation in NTB-P		21.3	14.6	21.3	23.2	19.7	20.0	
	0	0.0d	0.0	0.0d	0.0c	0.0c	0.0d	4.9
	40	25.0c	0.0	11.4c	3.0c	10.5c	10.0c	4.2
	80	80.0b	2.3	30.0b	19.9b	40.8b	28.6b	5.2
	120	75.0a	6.5	43.5a	42.1a	54.5a	44.3a	5.3

[a] Cropping systems are CTB-F, conventional tillage barley-fallow; NTB-F, no-tillage barley-fallow; NTB-P, no-tillage barley-pea; and NTCB, no-tillage continuous barley.

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

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Table 5. Analysis of variance for total N input and output, change in N level, and N balance with sources for cropping system, N fertilization rate, year, and their interactions.

Source	Total N input	Total N output	Change in N level	N balance
Cropping system (C)	***	**	NS	***
N fertilization rate (N)	***	***	***	***
C × N	NS	NS	NS	NS
Year (Y)	***	***	***	***
C × Y	**	***	***	***
N × Y	**	NS	*	*
C × N × Y	NS	NS	NS	NS

*Significant at $P \leq 0.05$

**Significant at $P \leq 0.01$

***Significant at $P \leq 0.001$; NS, not significant.

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Figures

Fig. 1. Annualized crop residue N returned to the soil and grain N removal, averaged across cropping systems and years, as affected by N fertilization rate.

Fig. 2. Estimated N inputs from soil N mineralization, atmospheric N deposition (rain + snow), N added from crop seed and nonsymbiotic N fixation in various cropping systems. Cropping systems are CTB-F, conventional till barley-fallow; NTB-F, no-till barley-fallow; NTB-P, no-till barley-pea, and NTCB, no-till continuous barley.

Fig. 3. Estimated N inputs from soil N mineralization, atmospheric N deposition (rain + snow), N added from crop seed and nonsymbiotic N fixation in various N fertilization rates.

Fig. 4. Total N input and output, change in N level, and N balance in various cropping system. Cropping systems are CTB-F, conventional till barley-fallow; NTB-F, no-till barley-fallow; NTB-P, no-till barley-pea, and NTCB, no-till continuous barley. Bars followed by different letters at the top are significantly at $P = 0.05$ by the least square means test.

Fig. 5. Total N input and output, change in N level, and N balance in various N fertilization rates.

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Fig. 6. Estimated N outputs from N losses due to denitrification, ammonia volatilization, plant senescence, N leaching, gaseous N (NO_x) emissions, and surface runoff in various cropping systems. Cropping systems are CTB-F, conventional till barley-fallow; NTB-F, no-till barley-fallow; NTB-P, no-till barley-pea, and NTCB, no-till continuous barley.

Fig. 7. Estimated N outputs from N losses due to denitrification, ammonia volatilization, plant senescence, N leaching, gaseous N (NO_x) emissions, and surface runoff in various N fertilization rates.

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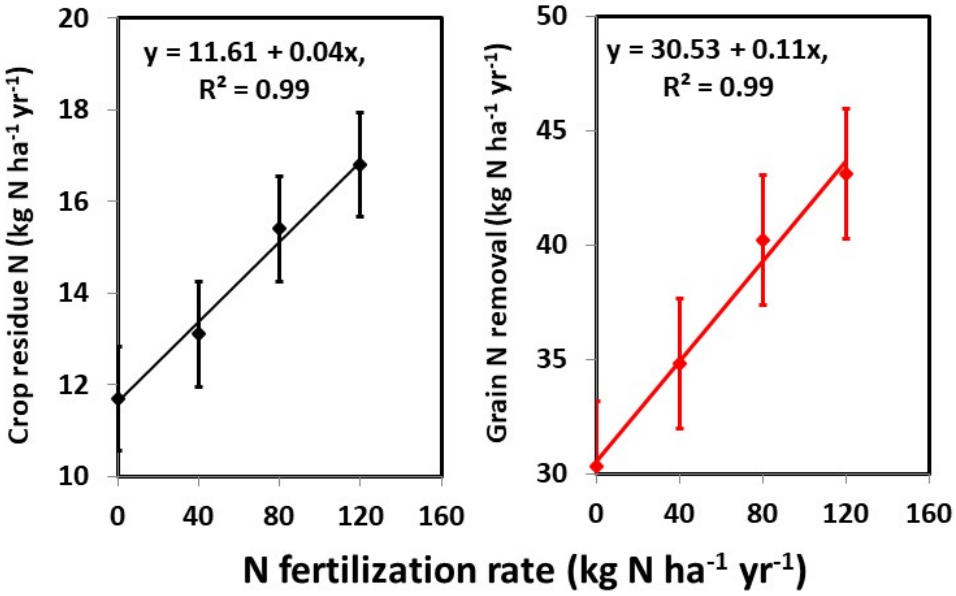


Fig. 1

Fig. 1. Annualized crop residue N returned to the soil and grain N removal, averaged across cropping systems and years, as affected by N fertilization rate.

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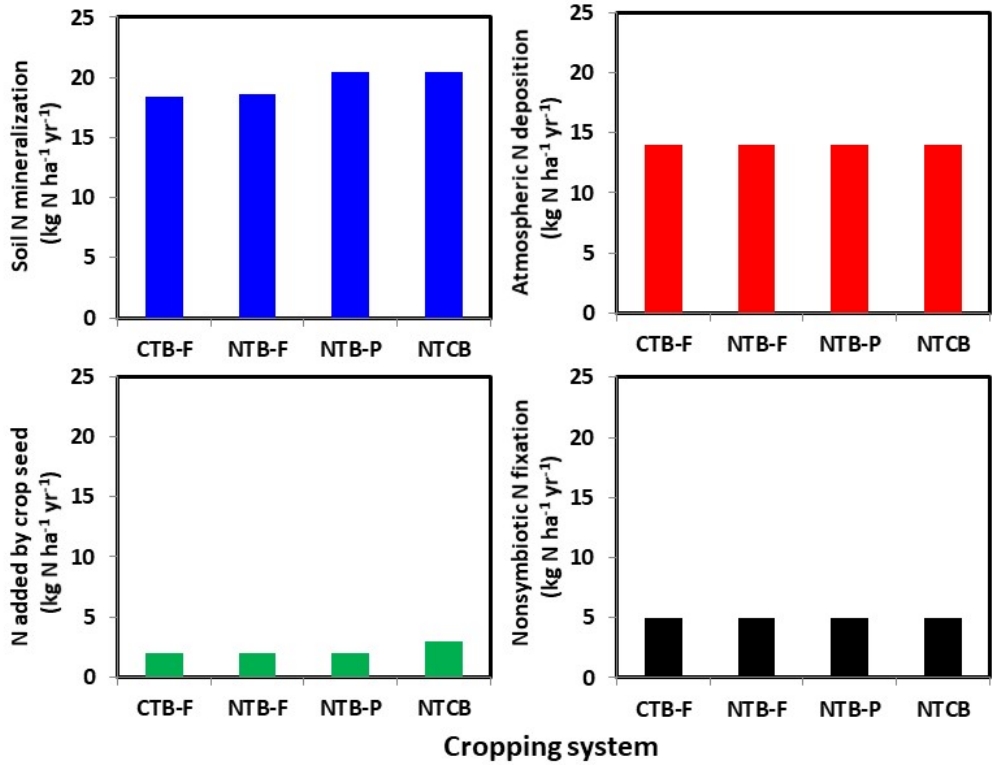


Fig. 2

Fig. 2. Estimated N inputs from soil N mineralization, atmospheric N deposition (rain + snow), N added from crop seed and nonsymbiotic N fixation in various cropping systems. Cropping systems are CTB-F, conventional till barley-fallow; NTB-F, no-till barley-fallow; NTB-P, no-till barley-pea, and NTCB, no-till continuous barley.

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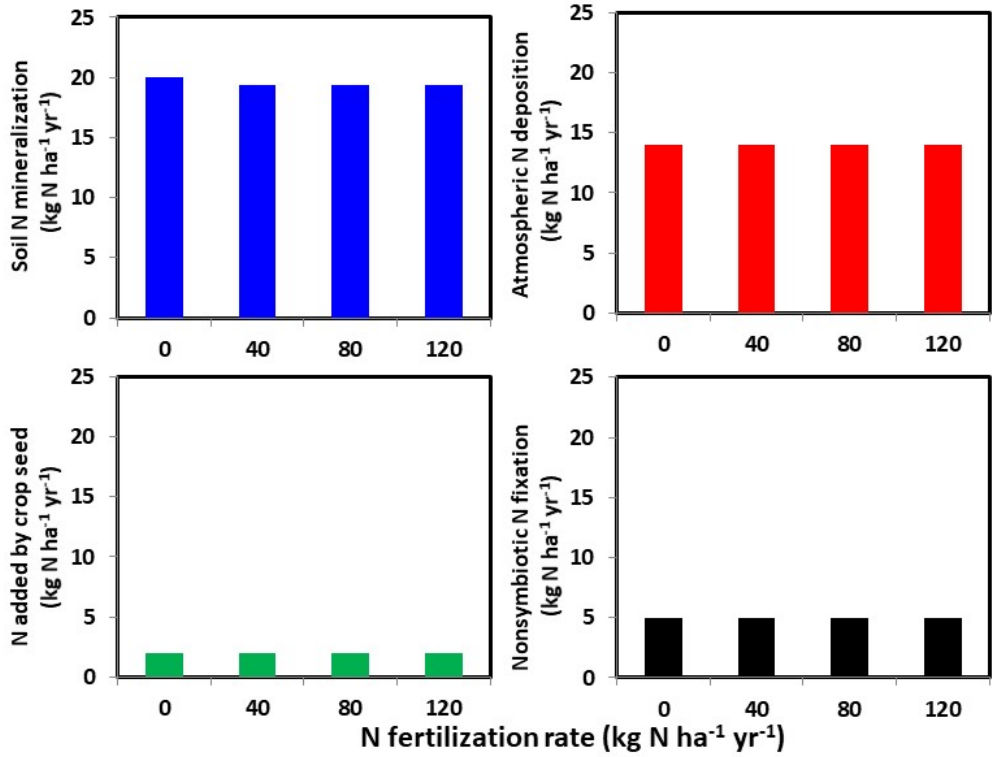


Fig. 3

Fig. 3. Estimated N inputs from soil N mineralization, atmospheric N deposition (rain + snow), N added from crop seed and nonsymbiotic N fixation in various N fertilization rates.

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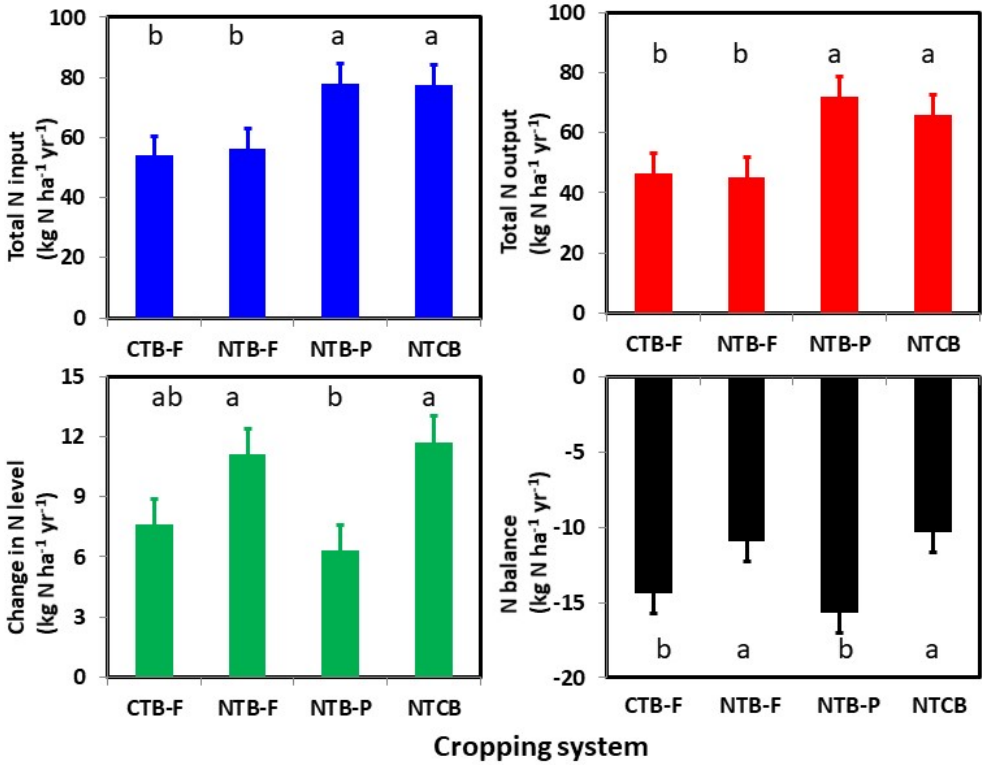


Fig. 4

Fig. 4. Total N input and output, change in N level, and N balance in various cropping system. Cropping systems are CTB-F, conventional till barley-fallow; NTB-F, no-till barley-fallow; NTB-P, no-till barley-pea, and NTCB, no-till continuous barley. Bars followed by different letters at the top are significantly at $P = 0.05$ by the least square means test.

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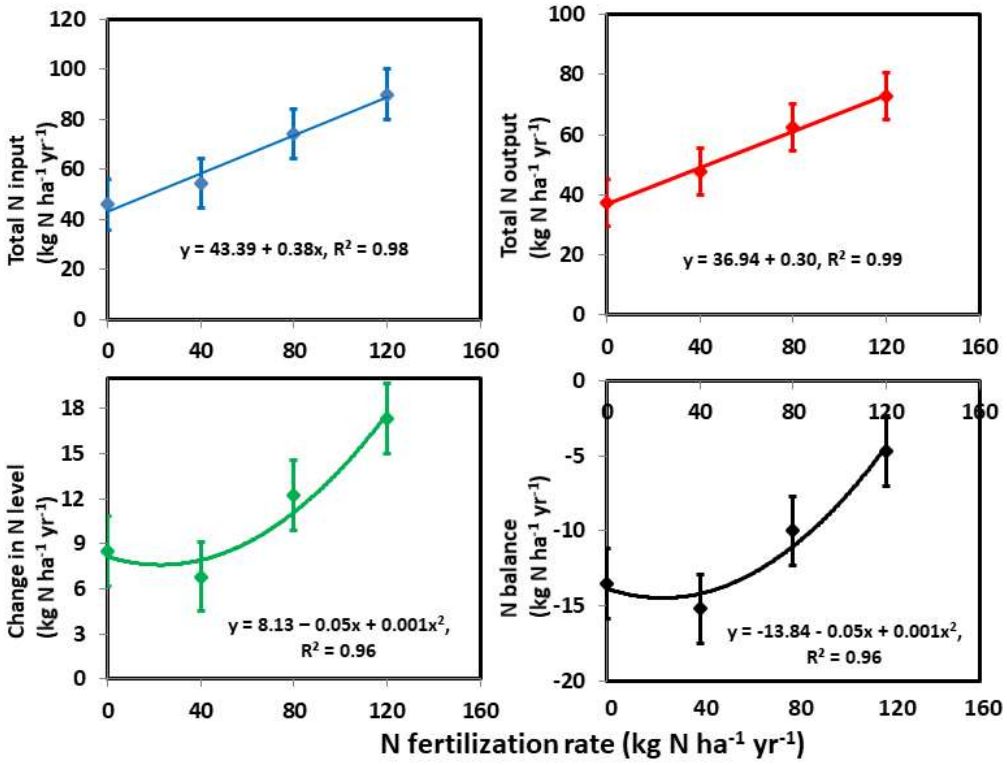


Fig. 5

Fig. 5. Total N input and output, change in N level, and N balance in various N fertilization rates.

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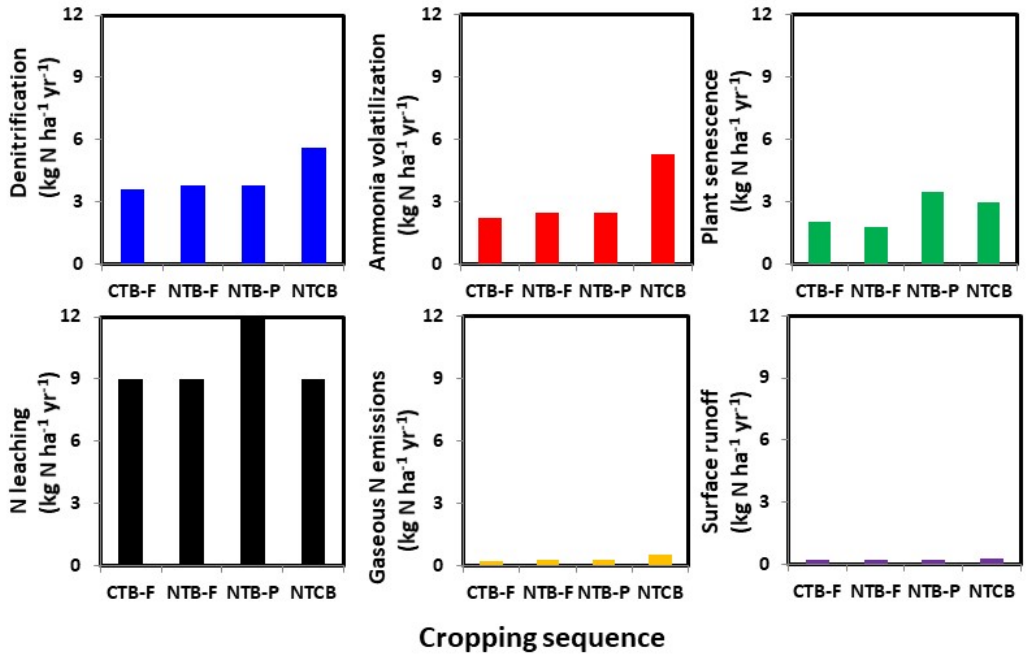


Fig. 6

Fig. 6. Estimated N outputs from N losses due to denitrification, ammonia volatilization, plant senescence, N leaching, gaseous N (NO_x) emissions, and surface runoff in various cropping systems. Cropping systems are CTB-F, conventional till barley-fallow; NTB-F, no-till barley-fallow; NTB-P, no-till barley-pea, and NTCB, no-till continuous barley.

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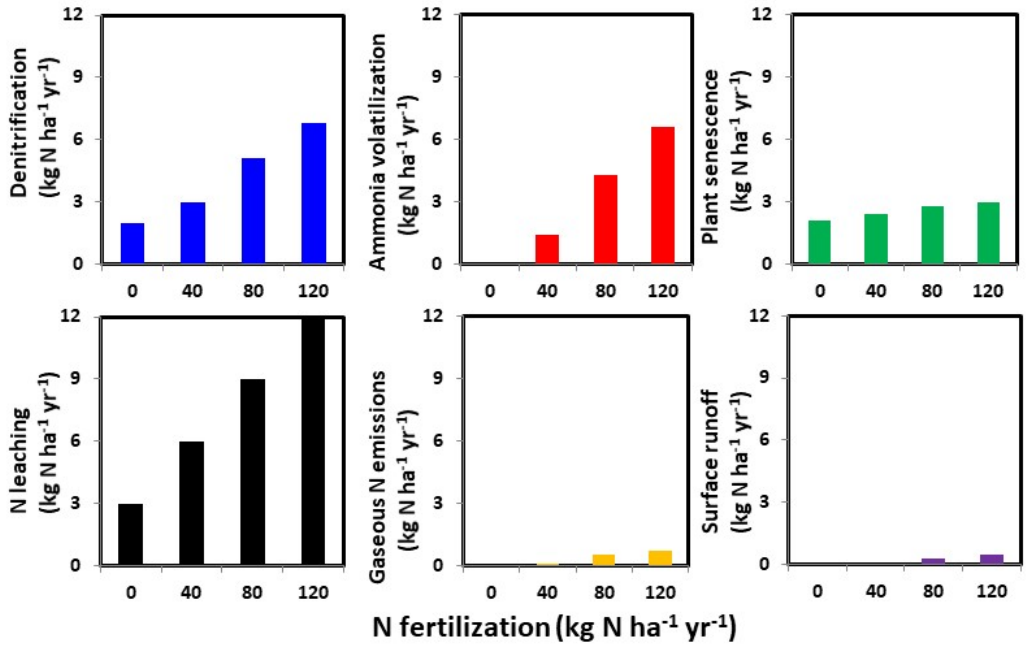


Fig. 7

Fig. 7. Estimated N outputs from N losses due to denitrification, ammonia volatilization, plant senescence, N leaching, gaseous N (NO_x) emissions, and surface runoff in various N fertilization rates.