Effect of manure under different nitrogen application rates on winter wheat production and soil fertility in dryland

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Abstract. Exploring an effective fertilization practice is crucial for achieving a sustainable dryland winter wheat cropping system. Following a split-plot design, this study was conducted to investigate the combined effect of manure (-M or +M; main plot) and various rates of nitrogen (N) fertilizer (0, 75, 150, 225, and 300 kg N ha\(^{-1}\); sub plot) on grain yield, water and N use efficiencies of winter wheat, and soil nutrients. The results showed that the treatments with manure improved the grain yield by 8%, and WUE by 10% relative to that without manure throughout the study years. The highest winter wheat yield and WUE were both recorded in the M+N225 treatment, which were not significantly different from those for M+N75 and M+N150 treatment. In contrast, high levels of N fertilizer (> 150 kg N ha\(^{-1}\)) combined with manure not only caused a reduction in the N use efficiency (NUE), but it also caused an increase in the soil residual nitrate-N (from 43.7 to 188.9 kg ha\(^{-1}\)) relative to without manure. After three years of continuous cropping, the treatment combining manure with 150 kg N ha\(^{-1}\) fertilizer had the highest SOM, available P and available K, which was 24%, 379% and 102% higher than that for unfertilized treatment (CK), and 10%, 267%, and 55% higher than that for without manure, respectively. Thus, the combination of manure (17.5 t ha\(^{-1}\) poultry or 30 t ha\(^{-1}\) pig manure) with 75-150 kg N ha\(^{-1}\) N fertilizer is recommended for improving winter wheat yield, water and N use efficiencies, and reducing soil nitrate-N residue as well.

1. Introduction

Water deficit and soil infertility are two major factors that limit cereal production in rainfed drylands that do not receive any supplemental water. The Loess Plateau in China had an average annual precipitation between 200-600 mm and a strong evaporation as a result of low infiltration and precipitation per event [1]. Therefore, it is characterized as a typical dryland. Furthermore, greater than 90% of the croplands in this region are rainfed. Winter wheat (Triticum aestivum L.) is one of the main cereal crops cultivated on the Loess Plateau, and it has a planting area of about 5 million hectares, which accounts for 40% of the total food crops cultivation area [2]. However, the winter wheat grain yields have been low and unstable for a long time, only averaging from 2.5 t ha\(^{-1}\) to 3.7 t ha\(^{-1}\) [3], which is much lower than the average yields in China. On the one hand, the irrational local cultivation and fertilization practices accelerates the degradation of soil quality, which results in a low soil organic matter content (SOM). Currently, two-thirds of the croplands in this region have an SOM below 1.0%. On the other hand, the rainfall distribution in this region is temporally uneven. For
example, 60% to 70% of the precipitation falls during July-September [4], which is when the winter wheat fields stay fallow. Drought often occurs during the growing season of winter wheat, and this water deficiency hastens maturation, shortens the grain-filling period, and reduces dry matter production, thereby resulting in low wheat yields on the Loess Plateau [5].

To combat this, fertilization is becoming crucial method to enrich soil fertility and “muster water” for meeting the crop growth demands and improving the crop production in the Loess Plateau [6]. However, the unadvised and excessive application of chemical fertilizer (especially N) by local farmers has brought a series of environmental issues, including eutrophication, groundwater contamination, and greenhouse gas emissions [7]. With the rapid development of agriculture, there is an increasing emphasis on soil fertility build-up and environmental protection to achieve the sustainability of dryland farming, rather than simply improving crop yields. Several studies have reported that the combined application of manure with inorganic fertilizers played an important role in improving soil nutrients, crop yields, fertilizer, and water use efficiency [8-11]. However, an unreasonable combination ratio of manure-N and inorganic-N does not result in high yields or water and N use efficiencies, but it instead caused a large amount of soil nitrate-N residue accumulation, which migrates down to deeper soil [12] and causes pollution in the underground water. Thus, the present study aimed to: (1) investigating the combined effect of manure with different rates of N fertilizer on grain yield, water and fertilizer use efficiencies of winter wheat, and soil nutrients; (2) exploring a locally optimal combination of manure and chemical N fertilizer for winter wheat production and environmental conservation. The results of this study will be theoretical basis for winter wheat production and soil fertility build-up in dryland.

2. Materials and methods

2.1. Experimental site

A 3-year winter wheat monoculture experiment was conducted from October 2011 to June 2014 in Bai Shui (109°58′N 35°18′E, 850 m asl) Shaanxi Province, China. Bai Shui County is located in the Loess Plateau, with an average annual temperature of 11.4°C and precipitation of 577.8 mm. The precipitation amounts during the 3 study years were 710.1 mm, 391.4 mm, and 603.8 mm in 2011-2012, 2012-2013, and 2013-2014, respectively. Based on the Generalized Precipitation Classification Scheme [13], 2011-2012 was categorized as a wet year, 2012-2013 was a dry year, and 2013-2014 was a normal year.

The soil at the experimental site is classified as Calcic Cambisols (FAO taxonomy), with a bulk density of ~1.30 g cm⁻³. The background soil sample collected from the 0–20 cm layer at the experimental site had 14.4 g kg⁻¹ of organic matter, 0.8 g kg⁻¹ of total N, 9.2 mg kg⁻¹ of Olsen-P, and 177.2 mg kg⁻¹ of available K.

2.2. Experimental design

A locally widely used winter wheat cultivar, ‘Jinmai - 47’, was used as the test crop. Two factors were included in this study: with manure and without manure (+M and -M), and five N application rates, including 0, 75, 150, 225, and 300 kg N ha⁻¹ (N0, N75, N150, N225, and N300). These 10 treatments were arranged in a split plot design with 4 replications, with the manure treatments as the main plot and the five N fertilizer rates as the sub plot. The non-fertilizer treatment was defined as the control (CK). The plot size was 6-m wide and 10-m long, and all the plots were arranged randomly in the field.

The manure-added areas (+M) were fertilized with a combination of manure and N fertilizer according to the five different application rates. Well-composted poultry manure and pig manure were collected from local farmers. Poultry manure was applied in the first year (2011-2012). In the latter two years (2012-2014) of the experiment, due to the scarcity of poultry manure resources, pig manure was applied. The application rates and nutrient contents of the poultry and pig manure are given in Table 1. The non-manure areas (-M) were only fertilized with the five rates of chemical N fertilizer. In addition, 90 kg P2O5 ha⁻¹ and 60 kg K2O ha⁻¹ were applied in all plots. The N fertilizer was applied as
urea: 70% of which was applied at sowing, and 30% was at the elongation stage in all treatments. Phosphorus (P) fertilizer was superphosphate, and potassium (K) fertilizer was sulfate of potash. All the fertilizers were evenly applied and incorporated into the top 0-20 cm soil layers before seeding.

Winter wheat was sown on 12th October, 17th October, and 15th October of each respective year by a seeding machine at a rate of 150 kg ha⁻¹ and with 20 cm-wide row spacing. The individual plots were plowed before sowing for seedbed preparation, and no irrigation was provided. All other field management practices were consistent with locally adopted practices during the three years study. The field was left fallow with low stubble after the winter wheat harvest, and the stubble and weeds were crushed and incorporated into the soil in late September before seedbed preparation.

### Table 1. Nutrient contents and application rates of the manures.

| Manure type          | Application rates (t ha⁻¹) | pH  | Organic matter (g kg⁻¹) | Total N (g kg⁻¹) | Total P (g kg⁻¹) | Total K (g kg⁻¹) |
|----------------------|-----------------------------|-----|-------------------------|------------------|------------------|------------------|
| Poultry manure       | 17.5                        | 8.7 | 47.5                    | 18.3             | 21.3             | 20.0             |
| Pig manure (2012-2013)| 30.0                        | 7.1 | 28.8                    | 8.0              | 12.5             | 14.5             |
| Pig manure (2013-2014)| 30.0                        | 7.6 | 25.3                    | 7.1              | 10.6             | 12.4             |

2.3. Sampling and sample analysis
In early June, Three quadrats covering a 4 m² area were selected randomly and manually harvested from the respective plot every study year. The crop was tied into bundles and then left in mesh bags for drying for about a week. After threshing, the air-dried grain was weighed to determine the grain yield. Additionally, crops which were randomly collected from the 3 by 1 m long rows were taken to the laboratory, and dried at 65 °C for 24 h. Then the oven-dried plant material were ground separately (grain and straw) with a grinder for nutrient analysis. The N contents in the samples were determined by the Kjeldahl method [14].

Three cores of soil samples (0-200 cm depth) in each plot were collected randomly by using an auger (inner diameter of 4.0 cm) before wheat sowing (early October) and after harvest (late June) every year. (This occurred in every year except for 2011, when only 7 cores were randomly selected in the whole experimental area before sowing). The soil from each 20 cm interval over the 0–200 cm layer was separated, and the soil from the same layer was mixed. The fresh soil samples were brought into the laboratory, and 10 g of each was used for estimating soil water content, by drying in an oven at 105°C for 12 hours for estimating the soil water content. Additionally, 5 g of each soil sample was extracted by 50 mL of 1 mol L⁻¹ KCl and shaking for 1 h for the soil nitrate-N estimation [15]. Soil samples for soil nutrient determination were collected at a depth of 20 cm at the end of the experiment (June 2014). The SOM was determined by oxidizing SOM in the soil samples with K₂Cr₂O₇ in concentrated sulfuric acid for 30 min followed by titration of the excess K₂Cr₂O₇ with ferrous-ammonium sulfate [16]. The Kjeldahl method was used for soil total N determination, the Olsen extraction method was used for available P estimation[17], and the available K was determined by a flame photometer [18].

2.4. Calculation methods
The soil water storage was calculated as:

\[ W = h \times \rho \times \theta \times 1000 \]

where \( h \) is the soil depth (cm); \( \rho \) is the soil bulk density (g cm⁻³), and \( \theta \) is the soil gravimetric water content (%).
The WUE was calculated as:

\[
WUE = \frac{Y}{ET} = \frac{Y}{W1 - W2 + P}
\]  

(2)

where \(Y\) is the grain yield \(\text{kg ha}^{-1}\); \(ET\) is the evapotranspiration \(\text{mm}\); \(W1\) is the soil water storage before the winter wheat planting \(\text{mm}\); \(W2\) is the soil water storage after the winter wheat harvest \(\text{mm}\); and \(P\) is the precipitation during the winter wheat growing season \(\text{mm}\).

The NUE was calculated as:

\[
NUE = \left(\frac{\text{Nitrogen uptake by the fertilized treatment} - \text{Nitrogen uptake in the control}}{\text{Total N applied}}\right) \times 100
\]  

(3)

Analysis of variance (ANOVA) was conducted to detect differences using SPSS 19.0 for Windows (SPSS Inc., Chicago, IL, USA). A one-way ANOVA was used to test for differences between the N application rates in the with manure group and without manure group, respectively. A two-way ANOVA was used to test for differences between groups with and without manure. Comparisons of means were performed using Duncan’s test.

3. Results

3.1. Grain yield

From table 2, the grain yield varied greatly among the study years, and its variation was consistent with the annual precipitation. More specifically, the wet year (2011-2012) produced the highest winter wheat yield, whereas the dry year (2012-2013) produced the lowest. Single inorganic fertilizer application improved the winter wheat yield by 16%, 26% and 13%, whereas the combination of manure and chemical fertilizer resulted in an increase of yield by 18%, 34% and 16% as compared to that of the CK treatment in 2011-2012, 2012-2013, and 2013-2014, respectively. In general, additional manure increased grain yield by a mean of 8% relative to that of single inorganic fertilizer application throughout the three experimental years.

| Treatment | 2011-2012 (kg ha\(^{-1}\)) | 2012-2013 (kg ha\(^{-1}\)) | 2013-2014 (kg ha\(^{-1}\)) |
|-----------|-----------------------------|-----------------------------|-----------------------------|
|           | -M  | +M  | -M  | +M  | -M  | +M  | -M  | +M  |
| N0        | 5156b | 5456b | 1906b | 2414b | 3805b | 4145b |
| N75       | 5722ab | 6004ab | 2147b | 2684a | 4164ab | 4410ab |
| N150      | 6300a  | 6325a  | 2504a  | 2760a  | 4459a  | 4595a  |
| N225      | 6267a  | 6345a  | 2532a  | 2854a  | 4520a  | 4679a  |
| N300      | 5656ab | 5950ab | 2489a  | 2595ab | 4192ab | 4264b  |
| Average   | 5820B | 6016A  | 2316B | 2661A  | 4228B | 4419A  |

Different lowercase letters (one-way ANOVA) and uppercase (two-way ANOVA) letters indicate significant differences at p < 0.05 (Duncan’s test).

The grain yield increased first and declined afterwards with the increasing N rate, and the highest grain yield was always observed in the M+N225 treatment during the study years, which was 6345 kg ha\(^{-1}\) in 2011-2012, 2854 kg ha\(^{-1}\) in 2012-2013, and 4679 kg ha\(^{-1}\) in 2013-2014. However, no significant differences were observe between M+N75, M+N150 and M+N225 treatments for grain yield. When the N rate was exceeded 225 kg N ha\(^{-1}\), increasing N input would not lead to a further increase in the winter wheat yield. The regression analysis indicated a parabolic relationship between the N application rate and the winter wheat grain yield (Figure 1). Maximum yield values in the –M group
were 6,294, 2,559, and 4,500 kg ha\(^{-1}\) corresponding to N rates of 176, 204, and 201 kg N ha\(^{-1}\), and in the +M group, the maximum yield values were 6,331, 2,825, and 4,648 kg ha\(^{-1}\) corresponding to N rates of 187, 179, and 173 kg N ha\(^{-1}\). The results revealed that, compared to that without manure, less N fertilizer is needed to achieve a higher maximum winter wheat yield after combining the fertilizer with manure. This effect was more obvious in the dry year when 70 kg N ha\(^{-1}\) fertilizer was reduced, but a 10% higher grain yield was achieved by additional manure.

3.2. Water use efficiency

Due to the scarcity of available soil water on drylands, improving the efficiency of water uptake by plants is crucial in promoting crop yields. “Mustering water with fertilizer” is an effective and important method for increasing the soil water uptake by plants and therefore improving water use efficiency (WUE).

Table 3 reveals that the ET was greatly affected by the precipitation, as the wet year resulted in the highest ET, whereas the dry year lead to the lowest. However, the effects of N rate and additional manure on ET were not significant. Compared to that of CK treatment, single inorganic fertilizer application increased WUE by 9%, 42%, and 20%; the combination of manure and inorganic fertilizer increased WUE by 14%, 62%, and 36% in 2011-2012, 2012-2013 and 2013-2014, respectively. In general, the WUE of the winter wheat increased in the order of: CK < single manure application < single N fertilizer application < combination of manure and N fertilizer. Additional manure increased WUE by 17% in 2012-2013, and 11% in 2013-2014. The highest WUE was recorded in the M+N225 treatment for 2012-2013 and 2013-2014, and it was 73% and 43% higher than that for CK and 29% and 16% higher than that for the N225 treatment in 2012-2013 and 2013-2014, respectively. However, the differences between M+N75, M+N150 and M+N225 treatments were not significant for WUE.

Figure 1. The variation of grain yield along with increasing N rate.
Table 3. The evapotranspiration (ET) and water use efficiency (WUE) affected by manure and N rate.

| Treatment | ET (mm) | WUE (kg ha⁻¹ mm⁻¹) |
|-----------|---------|---------------------|
|           | 2011-2012 | 2012-2013 | 2013-2014 | 2011-2012 | 2012-2013 | 2013-2014 |
|           | -M | +M | -M | +M | -M | +M | -M | +M | -M | +M |
| N0        | 542a | 580a | 255a | 245a | 344a | 336a | 9.5b | 9.4b | 7.9b | 10.4b | 10.1b | 11.3b |
| N75       | 550a | 573a | 247a | 251a | 323a | 336a | 10.0b | 10.5ab | 11.2a | 11.6ab | 12.3a | 13.8a |
| N150      | 524a | 560a | 238a | 251a | 326a | 348a | 12.0a | 11.3a | 11.2a | 11.6ab | 12.3a | 13.8a |
| N225      | 553a | 561a | 251a | 222a | 337a | 332a | 11.3ab | 11.3a | 10.6a | 13.7a | 12.5a | 14.5a |
| N300      | 565a | 583a | 228b | 228a | 335a | 343a | 8.9b | 10.2ab | 11.6a | 12.1a | 11.9ab | 12.4b |
| Average   | 547A | 571A | 244A | 239A | 333A | 339A | 10.3A | 10.5A | 10.1B | 11.8A | 11.7B | 13.0A |

Note: Different lowercase letters (one-way ANOVA) and uppercase (two-way ANOVA) letters indicate significant differences at p < 0.05 (Duncan’s test).

3.3. N use efficiency (NUE) of winter wheat and soil nitrate-N accumulation

After three years consecutive cultivation, the average N uptake of the winter wheat increased following the order of: CK < single manure application < single N fertilizer application < combination of manure and N fertilizer. Among all the treatments, M+N225 produced the highest N uptake, which was 59.4% higher than that for CK and 14% higher than that for N225 treatment. Combining manure with 75 and 150 kg N ha⁻¹ N fertilizer had higher NUE than those for single 75 and 150 kg N ha⁻¹ N fertilizer application, but when the N rate was exceeded 150 kg N ha⁻¹, additional manure would cause a decrease of NUE.

Table 4. N uptake and NUE affected by manure and N rate.

| Treatment | Shoot N uptake (kg ha⁻¹) | 0-200 cm soil nitrate-N residue (kg · hm⁻²) | NUE (%) |
|-----------|--------------------------|-------------------------------------------|--------|
|           | -M | +M | -M | +M | -M | +M | -M | +M |
| N0        | 206.1b | 226.8b | 79.6e | 109.2e | - | - |
| N75       | 261.3ab | 289.5ab | 165.7d | 192.1d | 24.5 | 27.9 |
| N150      | 287.1ab | 328.5a | 317.0c | 360.7c | 18.0 | 22.6 |
| N225      | 312.0a | 325.2a | 475.4b | 586.8b | 15.7 | 14.6 |
| N300      | 269.1ab | 277.5ab | 769.7a | 958.6a | 7.0 | 5.6 |
| Average   | 267.1B | 289.5A | 361.5B | 441.5A | 16.3A | 17.7A |

Note: Different lowercase letters (one-way ANOVA) and uppercase (two-way ANOVA) letters indicate significant differences at p < 0.05 (Duncan’s test).

The increasing N rate caused the NUE to gradually decline whereas the 0-200 cm soil nitrate-N residue to increase in both −M and +M groups. The differences in soil nitrate-N residue between −M and +M groups became more significant with the increasing N input. More specifically, when the N input was 150 kg N ha⁻¹, the difference in soil nitrate between −M and +M group was only 43.7 kg ha⁻¹, and when the N input increased to 300 kg N ha⁻¹, the difference came to 188.9 kg ha⁻¹.
3.4. Soil nutrients in 0-20 cm layer
As shown in table 5, after three years of consecutive planting, the soil nutrients (organic matter, total N, available P, and available K) decreased by different extents in the CK treatment, whereas the fertilization practices generally improved the soil nutrients as compared to the initial values before the study: The single N fertilization improved the SOM by 3%, total N by 6%, available P by 32%; The combination of manure and inorganic fertilizer improved the SOM by 18.9%, total N by 20%, available P by 268%, and available K by 9%. Among all the treatments, M+N150 resulted in the highest SOM, available P and available K, which was 24%, 379% and 102% higher than that for the CK treatment, and 10%, 267%, and 55% higher than that for N150 treatment.

Table 5. Effects of manure and different rates of N fertilizer on soil nutrients.

| Treatment | SOM (g·kg⁻¹) | Total N (g·kg⁻¹) | Available P (mg·kg⁻¹) | Available K (mg·kg⁻¹) |
|-----------|--------------|------------------|----------------------|----------------------|
|           | -M           | +M               | -M                   | +M                   | -M               | +M               |
| Before sowing | 14.3          | 0.81             | 9.23                 | 177.2                |
| N0        | 14.0b         | 14.6b            | 0.81a                | 0.89a                | 8.2b             | 28.7b            | 109.9bc          | 153.8b           |
| N75       | 14.5ab        | 16.9a            | 0.84a                | 0.95a                | 13.7a            | 32.0a            | 172.0a           | 206.0a           |
| N150      | 15.7a         | 17.3a            | 0.87a                | 0.96a                | 10.7b            | 39.3a            | 143.5ab          | 222.2a           |
| N225      | 14.7ab        | 17.0a            | 0.84a                | 0.99a                | 11.6ab           | 29.7b            | 89.9c            | 188.2ab          |
| N300      | 13.9b         | 16.8a            | 0.88a                | 1.06a                | 12.7a            | 40.1a            | 118.9bc          | 199.1ab          |
| Average   | 14.6B         | 16.5A            | 0.85B                | 0.97A                | 11.4B            | 34.0A            | 126.8B           | 193.9A           |

Note: Different lowercase letters (one-way ANOVA) and uppercase (two-way ANOVA) letters indicate significant differences at p < 0.05 (Duncan’s test).

4. Discussion
Previous studies have reported that the combination of manure and chemical fertilizer increased winter wheat yield relative to applying inorganic fertilizer alone [19-21]. In the present study, only rational combinations of manure and N fertilizer could achieve a high yield of winter wheat. Excessive N (>225 kg N ha⁻¹) input would not lead to a further increase in the winter wheat yield, which was consistent with previous studies [22-23]. Moreover, the present results revealed that the combination of manure and inorganic fertilizer was more effective for increasing the winter wheat yield and WUE during the dry year (15%) as compared to those of the wet (3%) and average year (5%). Wang et al. [24] reported similar results in a long-term experiment conducted in Gansu province, China (on the Loess Plateau). However, different results were reported by Hao et al., [25] who observed better yield improvement through additional manure during wet years. The opposite results may have manifested from varied soil conditions, nutrient contents in the manure, and the experimental period of different studies.

Water is one of the key factors that limits dryland farming development. Understanding the effect of fertilization practices on water use by crops and WUE is crucial for overcoming these limitations in dryland farming. In the present study, there were not any significant differences for ET between –M and +M groups, and this result is consistent with that of both Wang et al. [26] and Liu et al. [10]. Considering that there would be more water lost from transpiration to obtain higher yields, this observation indicates that combining manure with chemical fertilizer may enhance the transpiration of plants and decrease the water loss from evaporation through the soil surface. On the one hand,
Additional manure increased the numbers of ears, the aboveground biomass, and the canopies of winter wheat, which were effective barriers to prevent direct radiation, thus reducing water loss through evaporation [27]. On the other hand, the application of manure increased the soil infiltration rate, total porosity, water field saturated hydraulic conductivity, and soil water stable macro-aggregates (>0.25 mm) significantly, thereby enhancing the soil water holding capacity [10, 28]. However, the differences in the WUE between –M and +M groups were not significant in the first year; this is likely due to the prolonged salutary effect of manure on soil quality and productivity, and the differences could not be significant in just one year.

As agriculture has developed, the soil degradation and environmental pollution caused by N fertilizer has become increasingly serious over the years. As a result, the concerns for sustainable soil productivity and efficient use of N fertilizers have emerged as important issues. The present study showed that the combination of manure with N fertilizer increased the shoot N uptake as compared to applying chemical fertilizer alone. Liang et al. [29] found that the combined application of manure and chemical fertilizers significantly improved the immobilization of N fertilizer during the early stages of wheat growth when the N demand of the crop was low. Then, mineral N was released from the microbial N pool during the key process of wheat growth. This mechanism indicated that the combined application of manure and inorganic fertilizer increased the synchrony between the N supply and the crop demand, thus reducing N losses from agriculture. In addition, Li et al. [30] also reported an increase in the root activity of winter wheat after manure application, which improved the N uptake by the crop.

Fertilization practices offers a great opportunity to soil nitrate-N residue. In the present study, the NUE declined and the residual nitrate-N in the 0-200 cm soil layer increased gradually with increasing N fertilizer rate, which was consistent with some previous studies [31-32]. Furthermore, there would be more nitrate-N which accumulated in the soil in +M group compared to that in –M group as the N rate increased. However, M+N75 and M+N150 resulted in a comparable value of winter wheat yield and a higher NUE compared to that for N150 and N225, whereas the amount of residual nitrate-N in the soil profile was decreased, thus indicating the potential of manure to replace a portion of N fertilizer.

As a direct indicator of soil fertility, an improved SOM is important for achieving a sustainable dryland farming system. Several studies have reported the beneficial effect of a combined application of manure and inorganic fertilizer on SOM improvement [33-35]. The present results showed that, after three years of continuous application, the combined application of manure and chemical fertilizer improved the SOM by 18.9% relative to the initial value before the experiment, and by 15.6% relative to the single N fertilizer application. Additionally, inorganic N fertilization caused the SOM to increase, which is primarily because the larger biomass and root area stimulated by the N fertilizer left more crop residues in the soil, thereby increasing the SOM. Moreover, the manure group improved the soil available P and available K, which is primarily due to manure was rich in P and K, and enriched the soil fertility significantly.

5. Conclusions

Additional manure did not cause more soil water depletion than the without manure group did, but achieved a higher grain yield, which resulted in a higher WUE. However, only rational combinations of manure and chemical fertilizers was able to improve the N use efficiency of winter wheat and preventing more soil nitrate-N accumulation. The excessive N fertilizer (> 150 kg N ha⁻¹) combined with manure would cause a decrease in the NUE and the accumulation of soil residual nitrate-N as compared without manure. After three years of consecutive planting, the combination of manure with chemical N fertilizer significantly increased the SOM, total N, Olsen-P, and available K as compared to the initial values and the single N fertilizer application. The M+N150 treatment had a better effect on the soil fertility improvement than the other treatments.

Thus, considering the issue of environmental protection and soil fertility build-up, rather than simply improving crop yields, it can be concluded that a combination of 75-150 kg N ha⁻¹ of N
fertilizer with manure (17.5 t ha$^{-1}$ poultry manure or 30 t ha$^{-1}$ pig manure) should be recommended in order to achieve a sustainable winter wheat cropping system in a dryland.

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