Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district

Shiqi Yang1,2, Yongsheng Wang3,5, Ruliang Liu4, Lei Xing1,2 & Zhengli Yang1,2

Field experiments were conducted in rice-wheat rotation under conventional management to determine the effects of straw return ((half straw return, HS) and (total straw return, TS)) on crop yield, N uptake, soil properties and soil NO$_3$–N leaching. We found that straw return significantly increased crop yield and N uptake. TS significantly increased soil SOM at depths of 20 cm and 30 cm. Straw return had significantly increased soil NO$_3$–N leaching at a depth of 10 cm, whereas significantly decreased soil NO$_3$–N leaching at depths of 30 cm and 90 cm in the rice season. In wheat season, HS and TS performed better than conventional fertilization management without straw return in reducing soil NO$_3$–N leaching at depth of 90 cm. Soil NO$_3$–N leaching was significantly decreased through enhancing total N uptake, improving soil aggregation and decreasing soil NO$_3$–N concentration. Our results indicated that total straw return has the potential to increase crop yield, improve soil aggregation and decrease soil NO$_3$–N concentration, thus increasing total N uptake and reducing soil NO$_3$–N leaching in the rice-wheat rotation system of Ningxia Yellow river irrigation district. In the future, the long-term observation of crop yield and nitrate nitrogen leaching are necessary to identify the environmentally friendly straw return practices for rice-wheat rotation.

Synthetic nitrogen (N) fertilizer has enabled the doubling of world food production in the past four decades1. However, excessive fertilizer N inputs with decreasing N use efficiency have resulted in environmental pollution problems, such as leaching of nitrate and emission of nitrous oxide and ammonia2. China’s field experiments have shown low nitrogen use efficacy of 26–28% in 2001–2005 for major cereal crops3, relative to 52% in America and 68% in Europe4. Nitrogen leaching in China (13.7–347 kg N ha$^{-1}$) was significantly higher than that of Europe and America (4–107 kg N ha$^{-1}$)5. Nitrate nitrogen (NO$_3$–N) leaching has been of major concern in China recent decades due to its harmful effect on groundwater and human health6. Therefore, knowing how to effectively control soil NO$_3$–N leaching has become an important issue for the development of sustainable agriculture.

Soil NO$_3$–N leaching is greatly influenced by edaphic and climatic factors and agricultural management practices7. Straw are the primary source of N for the microbial biomass and for plants8. China produces the most crop residue in the world, approximately $8 \times 10^{10}$ kg yr$^{-1}$. However, 32.3% of crop residues are directly used as fuels, 27.1% are used as feed, 16.8% are discarded or burnt in open fields and only 14.1% are returned to the soil9. Straw return may improve soil structure and retain water10. Enhanced N mineralization and N use efficiency and reduce N leaching were reported after amending soil with straw in the previous studies7,11,12. However, greater amounts of straw return or deeper burial depth resulted in more water percolation and N leaching13. Appropriate straw return methods might be effective mitigation strategies for controlling N leaching in agricultural soils.

Ningxia irrigation region is one of the oldest and largest irrigation areas in northwest China, and sustains over 60% of the Ningxia population. From 1978 to 2009, total annual grain production and chemical fertilizer

---

1Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing, 100081, China. 2Key Laboratory of Agro-Environment and Climate Change, Ministry of Agriculture, Beijing, 100081, China. 3Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China. 4Ningxia Academy of Agriculture and Forestry Science, Yinchuan, 750002, China. 5Present address: No. 11, Datun road, Chaoyang district, Beijing, 100101, China. Correspondence and requests for materials should be addressed to Y.W. (email: wyswqj@163.com)
consumption increased 2.84 times and 4.24 times, respectively24. Currently, the conventional application rate of synthetic N fertilizer is 300 kg ha\(^{-1}\) yr\(^{-1}\) for paddy due to flooding irrigation. Higher N fertilizer rate will inevitably promote the N leaching into the water bodies, and lead to the non-point source pollution to the Yellow River25,26. Annual N loss in Qingtongxia area of Yellow River was 41.1 thousand tons, which is 1.52 times higher than that from the interzone point source pollution27. Both total N and ammonium N contents were increasing significantly with the increase of fertilizer application rates, especially since 1990s in Ningxia segment of the Yellow River18,19. It is essential to explore the agricultural management measures for reducing N leaching from farmland in Ningxia irrigation region.

Rice-wheat rotation is the dominant farming system in the Ningxia Yellow river irrigation region of China. Unfortunately, high N fertilizer application resulted in the higher N surplus in soil due to the reduced rice N uptake derived from soil in Ningxia Yellow river irrigation16. Many methods are studied to reduce N leaching losses, while not impairing the crop yields to ensure food security in Ningxia, including reducing and postponing N application30, side-dressing16, biochar and manure amendment21,22. In 2008, the total straw amounts of wheat, rice and maize from Ningxia province was estimated to be 70.48 × 10\(^7\) kg, 73.02 × 10\(^7\) kg and 164.94 × 10\(^7\) kg, respectively23. Previous study showed higher overall straw utilization rate of 68.9% in Ningxia provinces, compared with 35.0% of national level24. However, only 2.9% of total straw was returned to agricultural soil and used as fertilizer23. Return of straw with N fertilizer will has a widespread prospect in agricultural field management to increase productivity and reduce soil NO\(_3\)\(^-\)−N leaching in Ningxia area23,24. However, the effects of straw return on soil NO\(_3\)−N leaching of rice-wheat rotation system were not unclearly. We hypothesized that straw return will increase crop yields and reduce soil NO\(_3\)−N leaching in rich-wheat rotation, and this response will promoted with increasing amounts of straw return. In this study, our objectives were (1) to examine the effects of straw return on rice-wheat rotation system crop yields as well as soil NO\(_3\)−N leaching; and (2) to identify the environmental friendly straw return management practices for rice-wheat system in Ningxia region.

| Study site. | This study was conducted at Lingwu Farm (38°07′14″N, 106°17′43″E) in Yinchuan City, China. The temperate continental monsoon climate dominates the region, with a mean temperature of 8.9°C and a mean annual precipitation of 192.9 mm. The soil is classified as anthropogenic alluvial soil, with a soil texture of 18.25% clay, 53.76% silt, and 27.99% sand. The top soil (0–30 cm) organic matter is 10.58 g kg\(^{-1}\), the total N is 0.98 g kg\(^{-1}\), and the soil bulk density is 1.39 g cm\(^{-3}\). |
| --- | --- |

### Materials and Methods

**Experimental design and agricultural management.** The straw return experiment is a randomized block design with three treatments: CM (Conventional fertilization management without straw return), HS (Conventional fertilization management with half straw return, about 0.40 kg m\(^{-2}\) rice straw or 0.20 kg m\(^{-2}\) wheat straw), TS (Conventional fertilization management with total straw return, about 0.80 kg m\(^{-2}\) rice straw or 0.40 kg m\(^{-2}\) wheat straw). Each treatment was performed in triplicate. A total of 9 plots (10 m × 30 m) were established.

Urea was applied at 300 kg N ha\(^{-1}\) and 225 kg N ha\(^{-1}\) for rice and wheat, respectively, of which 10% was applied before winter irrigation, 50% was applied as a base fertilizer, 30% was applied at the tillering stage, and the remaining 10% was applied at the elongation stage. Double superphosphate and KCL were also applied as basal fertilizers at rates of 105 kg P\(_2\)O\(_5\) ha\(^{-1}\) and 60 kg K\(_2\)O ha\(^{-1}\), respectively. Rice and wheat straw was cut to 6–8 cm by harvester during the harvest period. Each plot was irrigated with an equal amount of water. Total frequency of water irrigation was 16 times and 4 times, with total amount of 14500 m\(^3\) ha\(^{-1}\) yr\(^{-1}\) and 4350 m\(^3\) ha\(^{-1}\) yr\(^{-1}\) for rice and wheat season, respectively (Table 1). Straw and fertilizers were broadcast on the soil surface and incorporated into the soil by plowing to a depth of approximately 10 cm before winter irrigation. Other crop management was consistent across plots in each crop season. The experiment was carried out over 2 years beginning in 2010 and ending in 2011.

### Soil NO\(_3\)−N losses measurement.** Soil NO\(_3\)−N leaching losses was measured by the method of exchange resin core31. Four tubes (stainless steel, 43 cm\(^2\) were installed at the desired depth (10, 20, 30 and 100 cm) below the soil surface for each treatment condition. About 2 cm soil was removal from the tube bottom after getting the intact soil core by the above tube. About 15 g of anion ion exchange resin (SIGMA, USA) was packed into nylon bag (41 cm\(^2\)) and put at the tube bottom. Primary soil was used to fill the tube bottom and prevent the resin bag being dropped32. Intact soil core was inserted and cultivated in situ without crop in it. Soil leachate NO\(_3\)−N was absorbed by anion ion exchange resin during migration in the soil profile and was desorbed using 2 M KCL solution. The NO\(_3\)−N leaching losses were calculated by multiplying the N concentration by the desorbed solution volume.

### Rice yield and N uptake. At crop maturity, crop aboveground biomass was estimated by manually harvesting three 0.5 m\(^2\) areas. Straw and grain were oven-dried to a constant weight at 70°C, weighed, finely ground, sieved, and analyzed for total N using the Kjeldahl method33. The uptake of N in straw and grain was calculated by

| Growth stage | Tilling (time) | Elongation (time) | Booting (time) | Filling (time) | Fallow (time) | Total volume (m\(^3\) ha\(^{-1}\)) |
| --- | --- | --- | --- | --- | --- | --- |
| Rice | 8 | 3 | 3 | 1 | 1 | 14500 |
| Wheat | 1 | 1 | 1 | 1 | 0 | 4350 |

**Table 1.** Frequency and total volume of water irrigation during rice-wheat rotation period.
compared with CM (Table 2).

respectively. In addition, total wheat N uptake was increased by 10.69% and 12.18% in HS and TS, respectively, increase induced by straw return on total rice N uptake was 10.43% and 22.02% for the HS and TS treatments.

Soil organic matter (SOM) and active soil organic matter (ASOM) was all calculated using the efficiency factor of depth of 10 cm (Fig. 1c). Furthermore, HS and TS treatments significantly decreased soil \( \text{NO}_3^- \) concentration, while significantly decreased wheat soil \( \text{NO}_3^- \) concentration at a depth of 30 cm (Fig. 1a). The lowest soil \( \text{NO}_3^- \) concentration was observed at a depth of 20–30 cm (Table 3).

Soil porosity in TS treatment was significantly higher than that of CM treatment at the 0–10 cm depth. However, the effects of straw return on soil bulk density and soil porosity were not significantly between the 10–20 cm and 20–30 cm depth (Table 3).

**Statistical analyses.** Repeated measures of analysis of variance (ANOVA) with the least significant difference (LSD) test were applied to examine the differences in soil \( \text{NO}_3^- \) concentration at various depths (Fig. 1b, Fig. 1d). The lowest soil \( \text{NO}_3^- \) concentration occurred in the TS treatment at a depth of 10 cm (Fig. 1c).

**Results**

**Crop yield and N uptake.** In the CM, the rice yield and wheat yield was 6358 kg ha\(^{-1}\) and 3749 kg ha\(^{-1}\), respectively. Straw return significantly increased the crop yield compared with the CM treatment for the HS and TS treatments (Table 2). Grain and straw N uptake increased with increasing straw return amount. The relative increase induced by straw return on total rice N uptake was 10.43% and 22.02% for the HS and TS treatments, respectively. In addition, total wheat N uptake was increased by 10.69% and 12.18% in HS and TS, respectively, compared with CM (Table 2).

**Soil properties.** Straw return significantly decreased soil bulk density at the 0–10 cm depth only (Table 3). Soil porosity in TS treatment was significantly higher than that of CM treatment at the 0–10 cm depth. However, the effects of straw return on soil bulk density and soil porosity were not significantly between the 10–20 cm and 20–30 cm depth (Table 3).

In rice season, relative to the CM, HS and TS increased rice soil TN concentration by 7.51% and 8.76% at a depth of 30 cm, respectively (Fig. 1a). The lowest soil \( \text{NO}_3^- \)–N concentration occurred in the TS treatment at a depth of 10 cm (Fig. 1c). Furthermore, HS and TS treatments significantly decreased soil \( \text{NO}_3^- \)–N concentration at a depth of 30 cm (Fig. 1c). In wheat season, straw return increased TN concentration, while significantly decreased wheat soil \( \text{NO}_3^- \)–N concentration at various depths (Fig. 1b, Fig. 1d).

Except for the depth of 10 cm, TS significantly increased SOM in the rice season (Fig. 2a). In the wheat season, SOM of TS treatment significantly higher than that of CM and HS treatments at a depth of 20 cm.

Table 2. Yield and N uptake under different experimental treatments (n = 3).

| Treatment | Crop yield (kg ha\(^{-1}\)) | Grain N uptake (kg ha\(^{-1}\)) | Straw N uptake (kg ha\(^{-1}\)) | Total N uptake (kg ha\(^{-1}\)) |
|-----------|----------------------------|---------------------------------|-------------------------------|-------------------------------|
| Rice      |                            |                                 |                               |                               |
| CM        | 6357 ± 136c                | 66.34 ± 1.72c                   | 55.10 ± 1.02c                 | 121.44 ± 2.74c                |
| HS        | 6952 ± 93b                 | 72.77 ± 1.39b                   | 61.34 ± 1.43b                 | 134.11 ± 1.81b                |
| TS        | 7447 ± 143a                | 76.20 ± 1.24a                   | 71.98 ± 2.32a                 | 148.18 ± 2.87a                |
| Wheat     |                            |                                 |                               |                               |
| CM        | 3749 ± 115b                | 79.72 ± 2.34c                   | 35.29 ± 0.13b                 | 115.01 ± 2.42b                |
| HS        | 4154 ± 84a                 | 88.34 ± 1.86a                   | 38.97 ± 0.70a                 | 127.31 ± 2.46a                |
| TS        | 4198.73 ± 86a              | 89.44 ± 1.99a                   | 39.57 ± 0.34a                 | 129.01 ± 2.33a                |

Table 3. Soil bulk density and porosity under different experimental treatments (n = 3).

| Treatment | Soil bulk density (g cm\(^{-2}\)) | Soil porosity |
|-----------|-----------------------------------|---------------|
|           | 0–10 cm | 10–20 cm | 20–30 cm | 0–10 cm | 10–20 cm | 20–30 cm |
| CM        | 1.53 ± 0.03a | 1.51 ± 0.05a | 1.59 ± 0.04a | 0.42 ± 0.02 b | 0.40 ± 0.04a | 0.41 ± 0.02a |
| HS        | 1.48 ± 0.02 b | 1.54 ± 0.02a | 1.60 ± 0.01a | 0.44 ± 0.01ab | 0.41 ± 0.05a | 0.38 ± 0.06a |
| TS        | 1.49 ± 0.02 b | 1.57 ± 0.03a | 1.65 ± 0.04a | 0.45 ± 0.02a | 0.39 ± 0.03a | 0.36 ± 0.03a |
significantly increased wheat SOM at a depth of 30 cm (Fig. 2b). The significantly difference of ASOM was only found at a depth of 20 cm with the highest value occurred in the HS and TS treatments in rice and wheat season, respectively (Fig. 2c-d).

Soil NO$_3^-N$ leaching. Soil NO$_3^-N$ leaching was significantly decreased with crop growth at various soil depths (Fig. 3, Table 4). The new soil NO$_3^-N$ leaching peak was occurred at depth of 90 cm in rice season (Fig. 3d). The averaged soil NO$_3^-N$ leaching decreased with the soil depth (Fig. 4).

Straw return had significantly increased soil NO$_3^-N$ leaching at a depth of 10 cm, whereas significantly decreased soil NO$_3^-N$ leaching at depths of 30 cm and 90 cm in the rice season (Fig. 4a). Furthermore, significant interactions were found between the observation date and straw return treatment, except for the depth of 90 cm (Table 4, $P < 0.001$). In wheat season, HS and TS showed significantly decreased soil NO$_3^-N$ leaching at depth of 90 cm, compared with CM (Fig. 4b). The significant interaction for soil NO$_3^-N$ leaching was only found at depth of 30 cm between observation date and straw return treatment (Table 4, $P < 0.001$).

Discussions

Effects of straw return on crop yield. The effects of straw return on crop yield is still under debate since field results across various pedo-climatic environments are inconclusive, partly due to the numerous and complex factors that affect the straw-derived N cycle under field conditions[36, 38]. Crop yield benefits from straw return are seen in N-restricted or over-fertilization in the North China Plain[31]. In our study, HS and TS treatments significantly increased the rice yield by 9.35% and 17.15%, respectively, while the increases in wheat yield elicited by HS and TS return were 10.80% and 12.00%, respectively (Table 2). Enhanced crop yields to straw return could be related to the following aspects. In Ningxia irrigation region, over use of N fertilizer in the rice-wheat rotation system has resulted in soil NO$_3^-N$ leaching out of root zone[16, 20]. The N immobilized by straw would be released across crop growing season, thus improving N uptake (Table 2) and crop yield[32, 39]. Yang et al. also suggested that ditch-buried straw return has the potential to increase crop N uptake and crop yield in the rice-wheat system through increased N retention in the soil. In addition, straw benefit the improvement of soil properties, such as soil bulk density, soil porosity and SOM (Table 3), and consequently promoting the improvement of crop yield[13, 32]. Therefore, our preliminary results revealed that crop yield improvement is attributed to both increased soil TN and additional nutrients supplement after straw return. However, the meta-analysis and long-term results revealed that incorporation of crop straw produced no significant trend in improving crop yield. Therefore, the effects of straw return on rice-wheat yields were needed further study[38, 39].
Figure 2. Arithmetic means of SOM and ASOM concentrations under the experimental treatments in rice (a,c) and wheat (b,d) season. Data are shown as means with standard errors (n = 3). Different letters below the columns mean significant difference among the treatments.

Figure 3. Variation of soil NO$_3$−N leaching at various soil depths under the experimental treatments. Data are shown as means with standard errors (n = 3). Different letters below the columns mean significant difference among the treatments. Date format is Year-Month-Date.
Effects of straw return on soil NO$_3^-$–N leaching. Organic amendments are often shown to increase soil nitrogen retention and reduce N leaching$^{35}$. In our study, the significantly reductions in soil NO$_3^-$–N leaching were observed at depths of 30 cm and 90 cm in rice season and at depth of 90 cm in wheat season (Fig. 4). This result would be expected and is in accord with several previous studies$^{11,13}$. First, the moderate increase in the N use efficiency may be associated with higher reduction rate of N leaching. The promotion of crop N uptake is critical to reduce N pollution in agro ecosystems due to minimizing surplus soil N$^{35}$. In the study area, evidence for the decreased soil NO$_3^-$–N leaching was provided by the increased total N uptake after straw return (Table 2). Second, large quantity of straw return may strongly physically absorb N and alter N spatial distribution in the soil profile. Wheat straw carries negative charges and shows good adsorptive capability for urea-N$^{37}$. Otherwise, straw fixed part of the NO$_3^-$–N and released organic acids during its decomposition and inhibited the transformation of NH$_4^+$–N to NO$_3^-$–N$^{38}$. In our experiment, straw return tended to increase TN concentration while decrease soil NO$_3^-$–N concentration in the upper 30 cm soil (Fig. 1). Thus more available N in the upper part of soil can be preferentially utilized by crops, and few soil NO$_3^-$–N leaching below the rooting zone. Third, the increased availability of carbon source following straw return, may stimulate the dissimilatory NO$_3^-$–N reduction to NH$_4^+$–N (DNRA) and therefore promoting N retention in soil and reducing soil NO$_3^-$–N leaching and runoff$^{39}$. Increased SOM and higher ASOM (Fig. 2) in our straw return treatments may have promote microbial growth and serve to immobilize N$^{40}$. Meanwhile, the large available carbon could prime nitrifies and denitrifies, which could contribute to N loss as gaseous emissions. Moreover, the high C/N ratio of straw incorporated into the soil can transform mineral N to organic N by immobilization$^{41}$. Finally, the extension of fungal hyphal by straw return could improve soil aggregation, thus enhancing water infiltration$^{42}$. The increased soil water holding capacity due to the reduced soil bulk density and increased soil porosity (Table 2) may have also reduced soil NO$_3^-$–N leaching. Overall, straw return reduced the soil NO$_3^-$–N leaching via promotion total N uptake, reducing availability of soil NO$_3^-$–N concentration and SOM-induced N immobilization. It is noted that the concentration of N fractions in irrigation water will influence soil properties and chemistry as well as soil NO$_3^-$–N leaching. In our study, this effect can be eliminated due to the same water source in Yellow River, equal irrigation time and amount for each plot (Table 1). In addition, reduced soil NO$_3^-$–N concentration suggests that the concentrations of soil dissolved organic N or NH$_4^+$–N may increase in the upper 30 cm. Therefore, effective managements such as minimized soil disturbance, lower winter irrigation in the fallow period are beneficial to keep soil N pools from loss via deep leaching or gases emission.

Table 4. Results of repeated measures ANOVA on the effects on straw return, date, and their interaction on soil NO$_3^-$–N leaching (n = 3).

| Source of variation | Depth (cm) | 10 | 20 | 30 | 90 |
|---------------------|-----------|----|----|----|----|
| Rice                | Date      | <0.001 | <0.001 | <0.001 | <0.001 |
| Treatment           | 0.317     | 0.631 | 0.013 | 0.011 |
| Date × Treatment    | 0.014     | 0.000 | <0.001 | 0.060 |
| Wheat               | Date      | <0.001 | <0.001 | <0.001 | 0.002 |
| Treatment           | 0.811     | 0.447 | 0.250 | 0.049 |
| Date × Treatment    | 0.117     | 0.683 | <0.001 | 0.338 |

Figure 4. Arithmetic means of soil NO$_3^-$–N leaching under the experimental treatments in rice (a) and wheat (b) season. Data are shown as means with standard errors (n = 3). Different letters below the columns mean significant difference among the treatments.
Conclusions

The effects of straw return on crop yield, N uptake, soil properties and soil NO$_3^-$–N leaching were investigated in rice-wheat rotation system in Ningxia Yellow river district. Straw return significantly increased N uptake, soil porosity, TN concentration, SOM and ASOM contents, but it significantly decreased soil bulk density and soil NO$_3^-$–N concentration. Straw return significantly increased crop yields and N uptake. Soil NO$_3^-$–N leaching was significantly decreased through enhancing total N uptake, improving soil aggregation and decreasing soil NO$_3^-$–N concentration. In summary, our study has shown that total straw return about showed a good promotion of crop yield and good reduction in soil NO$_3^-$–N leaching in the rice–wheat rotation system in Ningxia Yellow river irrigation district. However, this is only two years results with one rice-wheat rotation. The responses of crop yield and soil NO$_3^-$–N leaching to straw return were also influenced by the interannual variability in precipitation and temperature. Long-term study should be enhanced to identify the environmentally friendly straw return practices for rice-wheat rotation.

References

1. Tilman, D. Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *P Natl Acad Sci USA* 96, 5995–6000 (1999).
2. Ju, X. T. et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *P Natl Acad Sci USA* 106, 3041–3046 (2009).
3. Zhang, F. S., Cui, Z. L., Wang, J. Q. & Chen, X. P. Current status of soil and plant nutrient management in China and improvement strategies. *Chin Bull Bot.* 24, 687–694 (2007).
4. Ladha, J. K., Krupnik, T. J., Six, J., Kessel, C. V. & Pathak, H. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy.* 87, 85–156 (2005).
5. Zhang, Y. T. et al. Abbiometric analysis of status and trend of international research on field nitrogen application effects on nitrogen losses and water quality. *Acta Ecol Sin.* 36, 6664–6676 (2016).
6. Zhang, W. L., Tian, Z. X., Zhang, N. & Li, X. Q. Nitrate pollution of groundwater in northern China. *Agr Ecosyst Environ.* 59, 223–231 (1996).
7. Huang, T., Ju, X. T. & Zhang, H. Nitrate leaching in a winter wheat–summer maize rotation on a calcareous soil as affected by nitrogen and straw management. *Sci Rep-UK.* 7, 42247, https://doi.org/10.1038/srep42247 (2017).
8. Malhi, S. S., Nyborg, M., Solberg, E. D., Dyck, M. F. & Puuraven, D. Improving crop yield and N uptake with long-term straw retention in two contrasting soil types. *Field Crop Res.* 124, 378–391 (2011).
9. Bi, Y. Y. Study on straw resources evaluation and utilization in China. (Beijing, 2010).
10. Ling, Y. et al. Responses of rice production, milled rice quality and soil properties to various nitrogen inputs and rice straw incorporation under continuous plastic film mulching cultivation. *Field Crop Res.* 155, 164–171 (2014).
11. Wang, L. et al. Nitrogen and phosphorus leaching losses from intensively managed paddy fields with straw retention. *Agr Water Manage.* 141, 66–73 (2014).
12. Zhao, X., Wang, S. & Xing, G. Nitrification, acidification, and nitrogen leaching from subtropical cropland soils as affected by rice straw-based biochar: laboratory incubation and column leaching studies. *J. Soil Sediment.* 14, 471–482 (2014).
13. Yang, H. et al. Effects of ditch-buried straw return on water percolation, nitrogen leaching and crop yields in a rice-wheat rotation system. *J. Sci Food Agr.* 96, 1141–1149 (2015).
14. Ningxia Statistical Yearbook, (Beijing, 2011).
15. Zhang, A. P. et al. Using side-dressing technique to reduce nitrogen leaching and improve nitrogen recovery efficiency under an irrigated rice system in the upper reaches of Yellow River Basin, Northwest China. *J Integr Agr.* 15, 220–231 (2016).
16. Zhang, Q. W., Yang, Z. L., Zhang, H. & Yi, J. Recovery efficiency and loss of ISN-labelled urea in a rice–soil system in the upper reaches of the Yellow River basin. *Agr Ecosyst Environ.* 158, 118–126 (2012).
17. Li, Q. K., Li, H. E., Hu, Y. W. & Sun, J. Nitrogen loss in Qingtongxia irrigation area. *Agro-Environment Science.* 27, 683–686 (2008).
18. Yu, T. & Chen, J. S. Impacts of the agricultural development on the water quality and nitrogen pollution of the Yellow River-case of Ningxia Irrigation Area. *J. Arid Resour Environ.* 18, 1–7 (2004).
19. Yun, E., Li, Y., Yang, J. & Yang, Z. Investigation on simulation of dynamic distribution of COD and ammonia-nitrogen pollution in Ningxia segment of the Yellow River. *J. Ningxia University.* 26, 283–286 (2005).
20. Zhang, A. P., Liu, R. L., Gao, J., Yang, S. Q. & Chen, Z. Regulating N application for rice yield and sustainable eco-agro development in the upper reaches of Yellow river basin, China. *The Sci. World J.* 2014, 239–279 (2014).
21. Wang, T. S. et al. Biochar amendment reduces paddy soil nitrogen leaching but increases net global warming potential in Ningxia irrigation, China. *Sci Rep-UK.* 7, 15923, https://doi.org/10.1038/s41598-017-11734-w (2017).
22. Yang, S. Q., Wang, Y. S., Zhang, A. P. & Yang, Z. L. Effect of nitrate nitrogen leaching of paddy field based on Pig manure returning soil in the Yellow River irrigation area of Ningxia. *Acta Ecol Sin.* 34, 4572–4579 (2014).
23. Yang, G., Tang, Z. H., Shi, H. X. & Wang, Z. J. Utilization status and development strategies of straw resources in Ningxia. *J. Agr Resour Environ.* 27, 34–37 (2010).
24. Yang, Z. P., Guo, K. Q., Zhu, X. H., Yan, X. L. & Han, W. T. Straw resources utilizing industry and pattern. *Trans Chin Soc Agric Eng.* 17, 27–31 (2010).
25. Lu, W. T., Jia, Z. K., Gao, F., Li, Y. P. & Hou, X. Q. Effects of straw returning on soil water and crop productivity in the rainfed area of southern in Ningxia, China. *Agro-Environment Science.* 30, 93–99 (2011).
26. Wang, Y. S., Huang, J. & Yang, S. Q. The Influence of Rice Straw Returning on the Leaching Losses of the Nitrate Nitrogen in Ningxia Irrigation District, China. *Agro-Environment Science.* 30, 697–703 (2011).
27. Bao, S. D. Soil and agricultural chemistry analysis. (Beijing, 2000).
28. Xu, M. et al. Soil organic carbon active fractions as early indicators for total carbon change under straw incorporation. *Biol Fert Soils.* 47, 745–752 (2011).
29. Chen, Y. Y., Yang, K., Tang, W. J. & Zhao, L. Parameterizing soil organic carbon’s impacts on soil porosity and thermal parameters for Eastern Tibet grasslands. *Science China.* 55, 1001–1011 (2012).
30. Mu, X. et al. Responses of soil properties, root growth and crop yield to tillage and crop residue management in a wheat–maize cropping system on the North China. *Eur J Agron.* 78, 32–43 (2016).
31. Manevski, K. et al. Optimising crop production and nitrate leaching in China: Measured and simulated effects of straw incorporation and nitrogen fertilisation. *Eur J Agron.* 80, 32–44 (2016).
32. Malhi, S. S. et al. Long-term straw management and N fertilizer rate effects on quantity and quality of organic C and N and some chemical properties in two contrasting soils in Western Canada. *Biol Fert Soils.* 47, 785–800 (2011).
33. Yang, H. et al. Soil nitrogen retention is increased by ditch-buried straw return in a rice-wheat rotation system. *Eur J. Agron.* 69, 52–58 (2015).
34. Singh, Y., Singh, B. & Timsina, J. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. *Adv Agron.* 85, 269–407 (2005).
35. Xia, L. L., Wang, S. W. & Yan, X. Y. Effects of long-term straw incorporation on the net global warming potential and the net economic benefit in a rice-wheat cropping system in China. *Agr Ecosyst Environ.* **197**, 118–127 (2014).
36. Ding, Y. *et al.* Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water Air Soil Poll.* **213**, 47–55 (2010).
37. Wang, Y., Gao, B. Y. & Yue, W. W. Adsorption of nitrate from aqueous solution by modified corn residues. *Acta Sci Circumst.* **27**, 1458–1462 (2007).
38. Keeney, D. R. *Nitrogen management for maximum efficiency and minimum pollution, Nitrogen in agricultural soils*. 605–649 (Madison, 1982).
39. Wang, J., Zhu, B., Zhang, J. B., Müller, C. & Cai, Z. Mechanisms of soil N dynamics following long-term application of organic fertilizers to subtropical rain-fed purple soil in China. *Soil Biol Biochem.* **91**, 222–231 (2015).
40. Burger, M. & Jackson, L. E. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. *Soil Biol Biochem.* **35**, 29–36 (2003).
41. Hartmann, T. E. *et al.* Nitrogen dynamics, apparent mineralization and balance calculations in a maize - wheat double cropping system of the North China Plain. *Field Crop Res.* **160**, 22–30 (2014).
42. Peng, S. L., Guo, T. & Liu, G. C. The effects of arbuscular mycorrhizal hyphal networks on soil aggregations of purple soil in southwest China. *Soil Biol Biochem.* **57**, 411–417 (2013).

**Acknowledgements**

This project was supported by the National Water Pollution and Treatment Science and Technology Major Project (No. 2014ZX07201-009), and Funds for Young Scientists from Institute of Geographical Sciences and Natural Resources Research, CAS (No. Y6V60226YZ).

**Author Contributions**

Shiqi Yang and Yongsheng Wang designed the experiment and wrote the main manuscript, Yongsheng Wang, Ruliang Liu and Lei Xing conducted the field experiments and prepared the tables and figures, and Zhengli Yang contributed ideas.

**Additional Information**

**Competing Interests:** The authors declare no competing interests.

**Publisher’s note:** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit [http://creativecommons.org/licenses/by/4.0/](http://creativecommons.org/licenses/by/4.0/).

© The Author(s) 2018