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Replacing nitrogen in mineral fertilizers with nitrogen in maize straw increases soil water-holding capacity

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Soil water-holding capacity decreases due to long-term mineral fertilizer application. The objective of this study was to determine how replacing mineral fertilizer with maize straw affected the soil water retention curve, soil water content, soil water availability, and soil equivalent pore size. Replacement treatments in which 25% (S_{25}), 50% (S_{50}), 75% (S_{75}), and 100% (S_{100}) of 225 kg ha⁻¹ nitrogen from mineral fertilizer (CK) was replaced with equivalent nitrogen from maize straw were conducted for five years in the Loess Plateau of China. The Gardner model was used to fit the soil water retention curve and calculate the soil water constant and equivalent pore size distribution. The results indicated that the Gardner model fitted well. Replacing nitrogen from mineral fertilizer with nitrogen from straw increased soil specific water capacity, soil readily available water, soil delayed available water, soil available water, soil capillary porosity, and soil available water porosity over time. S_{25} increased field capacity and wilting point from the fourth fertilization year. S_{50} enhanced soil readily available water, soil delayed available water, soil available water, and soil available water porosity from the fifth fertilization year, whereas S_{25} and S_{75} increased these from the third fertilization year or earlier. Soil specific water capacity, soil readily available water, soil delayed available water, soil available water, soil capillary porosity, and soil available water porosity could better reflect soil water-holding capacity and soil water supply capacity compared with field capacity and wilting point.

Keywords Maize straw, Mineral fertilizer, Soil equivalent pore, Soil water availability, Soil water constant, Soil water retention curve

Plants absorb nitrogen and water for growth and metabolism. Nitrogen in plants mainly comes from soil. The relationship between nitrogen fertilizer and water is interdependent, and they work together in all aspects of plant growth. Appropriate amount of soil moisture content can promote nitrogen migration and transformation, and improve nitrogen availability, which is beneficial. Applying an appropriate amount of nitrogen can improve soil fertility and provide sufficient nutrients for plants¹. Water is the medium of nitrogen absorption and transport. Adequate water is beneficial to plant roots to absorb nitrogen and promote the effective use of nitrogen in plants. After nitrogen fertilization, soil microbial community structure changed and soil bacterial diversity decreased. Soil water status changed the composition and activity of the soil microbial community by affecting the transport of soil nutrients and soil properties^{2,3}. However, a large amount of nitrogen that is not absorbed and utilized by crops is lost through volatilization, nitrification–denitrification, runoff and leaching^{4,5}.

Straw is an important by-product of crop production and an important agricultural resource. How to understand the value of straw resources and the rational use of straw resources has become a focus of attention from all walks of life. As far as the current utilization of straw resources is concerned, returning to the field is the most important way of utilization. Straw incorporation increased soil organic matter⁶, and it significantly affected the

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physical, chemical and biological processes of soil, and had a significant effect on soil structure and function. Besides, straw incorporation improved soil structure⁷, enhanced soil nutrients⁸, and stimulated soil enzymatic activities⁹. The activities of soil hydrolases including β -1,4-xylosidase, β -d-cellulase and β -1,4-glucosidase were increased by straw returning in paddy fields¹⁰. Whereas long-term application of mineral fertilizer resulted in soil compaction¹¹ and caused soil degradation and seriously affected soil health. Besides, due to the inefficient use of nitrogen in crop and animal production, a large amount of nitrogen is lost, resulting in various environmental problems, including soil acidification, eutrophication water pollution and climate change, which are threatening our ecological environment^{12,13}. Therefore, replacing mineral fertilizers with maize straw is necessary.

Previous studies mainly focused on straw incorporation combined with mineral fertilizer^{8,14}. Wang¹⁵ showed that long-term application of mineral fertilizer and wheat straw returning increased soil available porosity and soil water-holding capacity. Pang¹⁶ found that two-year rotary tillage plus one-year deep tillage with maize straw returning and nitrogen fertilizer application increased the total porosity in the 0–20-cm soil layer and soil capillary porosity in the 10–30-cm soil layer compared with three-year rotary tillage with maize straw returning and nitrogen fertilizer application. Li¹⁷ observed that reduction in 1/6 chemical nitrogen fertilizer plus 6000 kg ha⁻¹ maize straw increased soil non-capillary porosity compared with 540 kg ha⁻¹ chemical nitrogen fertilizer application in the second and third fertilization years.

However, little is known about the effect of replacing nitrogen provided by mineral fertilizer with equivalent nitrogen provided by maize straw on the soil water retention curve and soil water availability. Thus, a five-year field experiment of equivalent nitrogen provided by different rates of maize straw incorporation and mineral fertilizer was established. We hypothesized that replacing nitrogen provided by mineral fertilizer with equivalent nitrogen provided by maize straw would enhance soil porosity, thereby increasing field capacity and soil water availability, and decreasing wilting point. The objective of this study was to evaluate the effects of replacing nitrogen from mineral fertilizer with equivalent nitrogen from maize straw on the soil water retention curve, soil water content, soil water availability, and soil equivalent pore size.

Materials and methods

Site description and experimental design

A five-year field experiment was performed using loam (sand 39.8%, silt 31.1%, and clay 29.1%)¹⁸ under maize cultivation in 2016–2020 at the Dongyang Research Station of Shanxi Agricultural University, Jinzhong, Shanxi, China (37° 56' N, 112° 69' E; 800 m altitude). The mean annual air temperature was 9.8 °C. The mean minimum air temperature of the coldest month (January) was -6.1 °C, and the mean maximum air temperature of the hottest month (July) was 28.1 °C. The experimental site was characterized by low and erratic rainfall with droughts occurring at different stages of maize growth. The long-term mean annual rainfall at the site was 430.2 mm and the mean annual evaporation was 1860.1 mm. The rainfall was 352.4, 308.0 and 572.1 mm during 2018, 2019 and 2020, respectively. Analysis of soil samples taken from the same experimental area in April 2016 showed that the top 20 cm of soil was characterized as follows: pH 8.4, soil organic matter 13.0 g kg⁻¹, total nitrogen 1.3 g kg⁻¹, total phosphorus 0.9 g kg⁻¹, total potassium 27.1 g kg⁻¹, available nitrogen 51.2 mg kg⁻¹, available phosphorus 7.7 mg kg⁻¹, and available potassium 176.4 mg kg⁻¹.

The field experiment used a completely randomized block design with five treatments and three replicates in a 5 × 6 m plot. Nitrogen provided by maize straw instead of 0%, 25%, 50%, 75%, and 100% of 225 kg ha⁻¹ nitrogen provided by mineral fertilizer were conducted in 2016–2020. The five treatments were as follows: (i) application of 100% of 225 kg ha⁻¹ nitrogen provided by mineral fertilizer only (CK); (ii) application of 25% (56.25 kg ha⁻¹) of 225 kg ha⁻¹ nitrogen provided by maize straw in combination with 75% (168.75 kg ha⁻¹) of 225 kg ha⁻¹ nitrogen provided by mineral fertilizer (S₂₅); (iii) application of 50% (112.50 kg ha⁻¹) of 225 kg ha⁻¹ nitrogen provided by maize straw in combination with 50% of 225 kg ha⁻¹ nitrogen provided by mineral fertilizer (S₅₀); (iv) application of 75% of 225 kg ha⁻¹ nitrogen provided by maize straw in combination with 25% of 225 kg ha⁻¹ nitrogen provided by mineral fertilizer (S₇₅); and (v) application of 100% of 225 kg ha⁻¹ nitrogen provided by maize straw only (S₁₀₀). Maize straw was incorporated at a 0–15 cm soil depth in each experimental year in late October. The 105 kg ha⁻¹ phosphorus provided by mineral fertilizer was applied to CK. Replacement treatments applied phosphorus provided by mineral fertilizer with 105 kg ha⁻¹ minus the phosphorus content of maize straw incorporated into soil. The mineral nitrogen and phosphorus fertilizers were applied separately as basal fertilizers before sowing maize. Urea and monoammonium phosphate were also applied. In each experimental year, the Dafeng 30 maize variety was planted at a rate of 49,500 plants ha⁻¹ in late April or early May and harvested in late September.

Sampling and analysis methods

Soil samples used for measuring the soil water retention curve were collected with a cutting ring at the plow layer after maize harvest. The soil samples were saturated slowly (> 24 h), weighed, and finally put into the CR22N high-speed refrigerated centrifuge (Hitachi Co.) to perform the soil water retention curve measurements starting from full saturation at 20 °C. The soil sample weight was measured at 10, 30, 50, 80, 100, 300, 500, 800, 1000, and 1500 kPa. Subsequently, the soil samples were oven-dried at 105 °C for 24 h. The volumetric water content at different suction levels was calculated using the equation:

$$\theta = \frac{V_W}{V} = \frac{W_S - W_o}{\rho \times V} \quad (1)$$

where θ is the soil volumetric water content at a certain suction (cm³ cm⁻³), V_W is the volume of water of the soil sample at a certain suction (cm³), V is the volume of the soil sample with 100 cm³ (cm³), W_S is the soil sample

weight under a certain suction (g), W_o is the soil sample weight after oven-drying (g), and ρ is the water density with 1 g cm^{-3} (g cm^{-3})¹⁹.

The Gardner model was used to fit the acquired data in Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, USA) as follows²⁰:

$$\theta = A \times S^{-B} \quad (2)$$

Soil specific water capacity was derived from formula (2), and it was defined as

$$C = A \times B \times S^{-(B+1)} \quad (3)$$

where θ is the soil volumetric water content ($\text{cm}^3 \text{ cm}^{-3}$), S is the soil water suction (kPa), A and B are dimensionless parameters related to the curve shape, and C is the soil specific water capacity (kPa^{-1})²¹.

The field capacity, soil volumetric water content at 600 kPa, and wilting point were calculated by the Gardner model at 33, 600, and 1,500 kPa, respectively²².

Soil readily available water, soil delayed available water, and soil available water content were defined as

$$\theta_r = \theta_f - \theta_{600} \quad (4)$$

$$\theta_d = \theta_{600} - \theta_w \quad (5)$$

$$\theta_a = \theta_f - \theta_w \quad (6)$$

where θ_r is the soil readily available water content ($\text{cm}^3 \text{ cm}^{-3}$), θ_f ($\text{cm}^3 \text{ cm}^{-3}$) is the field capacity, θ_{600} ($\text{cm}^3 \text{ cm}^{-3}$) is the soil volumetric water content at 600 kPa, θ_d ($\text{cm}^3 \text{ cm}^{-3}$) is the soil delayed available water content, θ_w ($\text{cm}^3 \text{ cm}^{-3}$) is the wilting point, and θ_a ($\text{cm}^3 \text{ cm}^{-3}$) is the soil available water content²².

The pore size range of soil capillary porosity was 0.03–0.1 mm and that of soil available water porosity was 0.002–0.06 mm¹⁹. The ranges of water suction of soil capillary porosity and soil available water porosity were 3–10 kPa and 5–150 kPa, respectively²². The soil volumetric water content at 3, 5, 10, and 150 kPa was calculated using formula (2). Soil capillary porosity was the soil volumetric water content at 3 kPa minus the soil volumetric water content at 10 kPa, multiplied by 100%. Soil available water porosity was the soil volumetric water content at 5 kPa minus the soil volumetric water content at 150 kPa, multiplied by 100%²².

Statistical analysis

Analysis of variance (ANOVA) was performed using SAS 6.2 for Windows. The significance of treatment effects in each year was determined using the F-test. Multiple comparisons of means were performed using Duncan's multiple range test²³ at $P \leq 0.05$. IBM SPSS statistics 27 and R language were used for principal component analysis (PCA) analysis.

Plant materials statement

The experiment complied with relevant institutional, national, and international guidelines and legislation.

Results

Soil water retention curve

The Gardner model²⁰ was used to fit the measured data of the soil water retention curve. The points were the measured values, whereas the lines were the fitted values in Fig. 1. The soil water content of each treatment showed a rapid decreasing trend when the water suction was lower than 100 kPa but a slowly decreasing trend when the water suction was greater than 100 kPa.

The fitting coefficient R^2 of the soil water retention curve of each treatment was above 0.950 (Table 1). The fitting effect was good. Parameter A determined the height of the curve and the level of the water-holding capacity. The larger the value of A , the stronger the water-holding capacity²⁴. S_{100} had the highest value of parameter A , followed by S_{75} , whereas parameter A with S_{25} and S_{50} was lower than that with CK in 2018. S_{25} had the highest value of parameter A , followed by S_{75} , whereas parameter A with S_{50} and S_{100} was lower than that with CK in 2019. S_{75} had the highest value of parameter A , followed by S_{25} , S_{50} , S_{100} , and CK in 2020. Thus, replacement treatments could increase soil water-holding capacity over time.

Soil specific water capacity

The soil specific water capacity at 100 kPa soil water suction reflected soil water supply capacity well²⁵. S_{50} decreased soil specific water capacity by 5.93% compared with CK, whereas S_{75} and S_{100} increased it by 19.16% and 24.30%; by 14.28% and 19.21%; and by 26.67% and 32.14% compared with CK, S_{25} , and S_{50} , respectively, in 2018 (Fig. 2). Soil specific water capacity with S_{25} was 10.84% higher than that with S_{50} in 2018.

S_{50} decreased soil specific water capacity by 21.64% compared with CK. However, S_{25} and S_{75} increased soil specific water capacity by 14.90% and 8.50%, respectively, compared with CK; and by 46.63% and 38.46%, respectively, compared with S_{50} ; and by 16.95% and 10.43%, respectively, compared with S_{100} in 2019. Soil specific water capacity with S_{100} was 25.38% higher than that with S_{50} in 2019.

Replacement treatments increased soil specific water capacity in 2020. S_{50} , S_{75} , and S_{100} increased soil specific water capacity by 13.87%, 16.81%, and 7.60%, compared with CK in 2020. Soil specific water capacity with S_{50} and S_{75} was 10.41% and 13.27% higher than that with S_{25} , and 5.83% and 8.57% higher than that with S_{100} , in 2020.

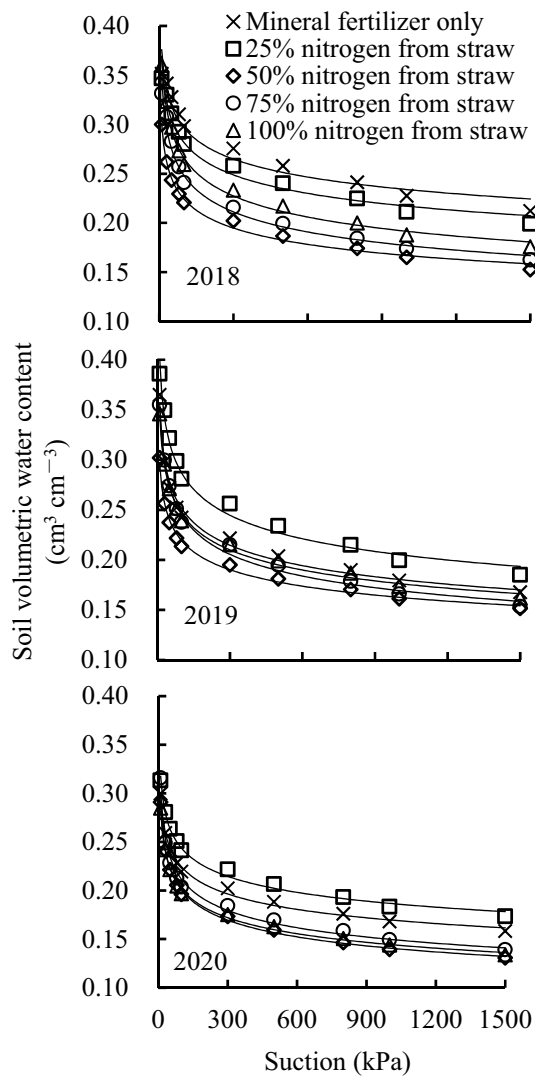


Figure 1. Soil water retention curve as a function of the different replacement treatments in 2018–2020.

Years	Treatments	A	R ²
2018	Mineral fertilizer only	0.4765	0.950
	25% nitrogen from straw	0.4742	0.972
	50% nitrogen from straw	0.4047	0.993
	75% nitrogen from straw	0.4872	0.981
	100% nitrogen from straw	0.5129	0.991
2019	Mineral fertilizer only	0.4899	0.987
	25% nitrogen from straw	0.5616	0.985
	50% nitrogen from straw	0.3996	0.993
	75% nitrogen from straw	0.5153	0.993
	100% nitrogen from straw	0.4813	0.995
2020	Mineral fertilizer only	0.3925	0.994
	25% nitrogen from straw	0.4143	0.993
	50% nitrogen from straw	0.4088	0.997
	75% nitrogen from straw	0.4227	0.982
	100% nitrogen from straw	0.3936	0.996

Table 1. Parameters in the modeling of the soil water retention curve as a function of the different replacement treatments in 2018–2020. A and B are dimensionless parameters related to the curve shape.

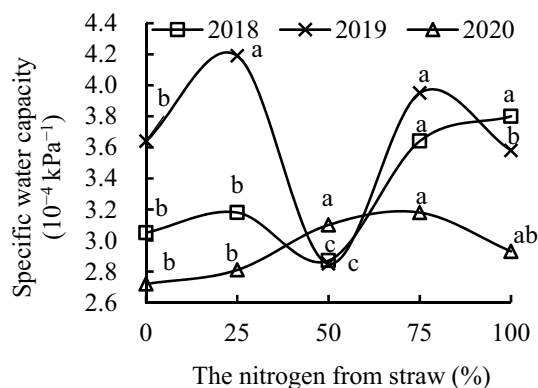


Figure 2. Specific water capacity of soil at 100 kPa as a function of the different replacement treatments in 2018–2020.

Thus, the replacement of nitrogen from mineral fertilizer with equivalent nitrogen from maize straw increased soil water supply capacity over time.

Soil water constant

Compared with CK, S_{25} slightly decreased field capacity, whereas S_{50} , S_{75} , and S_{100} decreased it by 22.17%, 12.33%, and 6.41%, respectively, in 2018 (Fig. 3). S_{25} increased field capacity by 14.23% and 7.78%, whereas S_{75} slightly decreased it, and S_{50} decreased it by 14.06% and 7.20% in 2019 and 2020, respectively. S_{100} slightly decreased field capacity in 2019 and decreased it by 7.78% in 2020.

S_{25} , S_{50} , S_{75} , and S_{100} decreased the wilting point by 7.49%, 29.25%, 25.86%, and 19.66%, respectively, compared with CK in 2018 (Fig. 4). The wilting point with S_{25} was 13.79% and 10.31% higher than that with CK in 2019 and 2020, respectively. Relative to CK, S_{50} and S_{75} decreased the wilting point by 9.02% and 6.48%, respectively, in 2019, and by 18.15% and 12.90%, respectively, in 2020. S_{100} slightly decreased the wilting point in 2019, and decreased it by 15.86% in 2020 compared with CK.

S_{100} had the highest soil readily available water, soil delayed available water, and soil available water, followed by S_{75} in 2018 (Figs. 5, 6, 7). S_{100} increased soil readily available water, soil delayed available water, and soil available water by 23.08%, 13.51%, and 21.11%, respectively, compared with CK; by 31.67%, 27.92%, and 30.80%, respectively, compared with S_{50} ; and by 18.25%, 11.50%, and 16.89%, respectively, compared with S_{25} in 2018. S_{75} increased soil readily available water, soil delayed available water, and soil available water by 17.83%, 8.11%, and 15.83%, respectively, compared with CK; by 26.06%, 21.83%, and 25.10%, respectively, compared with S_{50} ; and by 13.21%, 6.20%, and 11.80%, respectively, compared with S_{25} in 2018. S_{25} increased soil readily available water, soil delayed available water, and soil available water by 11.35%, 14.72%, and 11.90%, respectively, compared with S_{50} , and slightly increased these compared with CK, whereas S_{50} decreased these by 6.53%, 11.26%, and 7.41%, respectively, compared with CK in 2018.

S_{25} had the highest soil readily available water, soil delayed available water, and soil available water, followed by S_{75} in 2019. S_{25} increased soil readily available water, soil delayed available water, and soil available water by 14.91%, 14.52%, and 14.83%; by 46.05%, 41.54%, and 45.16%; by 6.30%, 9.52%, and 6.90%; and by 16.98%, 16.46%, and 16.88% compared with CK, S_{50} , S_{75} , and S_{100} , respectively, in 2019. S_{75} increased soil readily available water, soil delayed available water, and soil available water by 8.09%, 4.56%, and 7.42%, respectively, compared

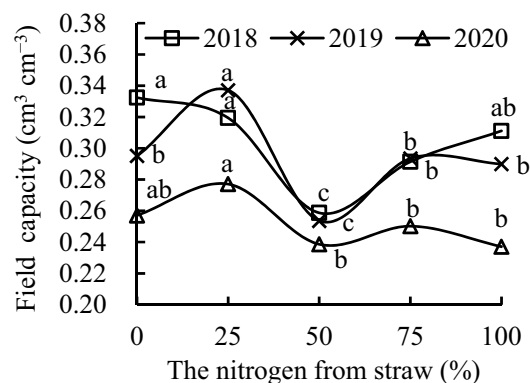


Figure 3. Field capacity as a function of the different replacement treatments in 2018–2020.

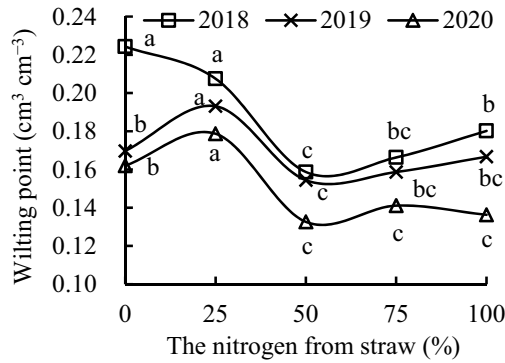


Figure 4. Wilting point as a function of the different replacement treatments in 2018–2020.

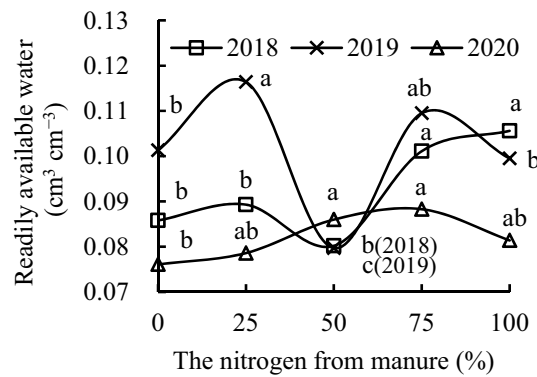


Figure 5. Readily available water content as a function of the different replacement treatments in 2018–2020.

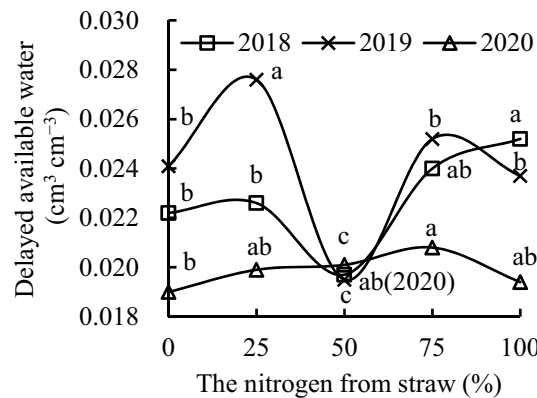


Figure 6. Delayed available water content as a function of the different replacement treatments in 2018–2020.

with CK; by 37.39%, 29.23%, and 35.79%, respectively, compared with S_{50} ; and by 10.05%, 6.33%, 9.33%, respectively, compared with S_{100} in 2019. S_{50} decreased soil readily available water, soil delayed available water, and soil available water by 21.32%, 19.09%, and 20.89%, respectively, whereas S_{100} slightly decreased these compared with CK in 2019.

Replacement treatments could increase soil readily available water, soil delayed available water, and soil available water in 2020. S_{75} had the highest soil readily available water, soil delayed available water, and soil available water, followed by S_{50} in 2020. S_{75} increased soil readily available water, soil delayed available water, and soil available water by 16.03%, 9.47%, and 14.72%, respectively, compared with CK; by 12.34%, 4.52%, and 10.76%, respectively, compared with S_{25} ; and by 8.48%, 7.22%, and 8.23%, respectively, compared with S_{100} in 2020. S_{50} increased soil readily available water, soil delayed available water, and soil available water by 13.01%, 5.79%, and

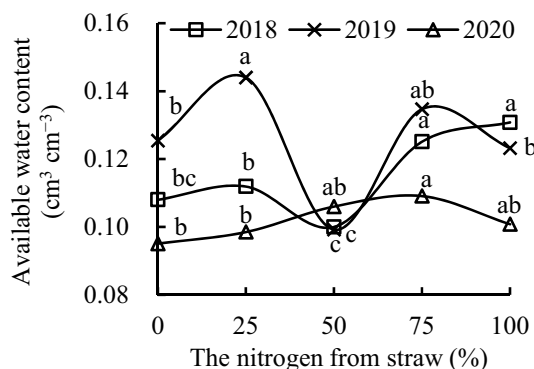


Figure 7. Available water content as a function of the different replacement treatments in 2018–2020.

11.46%, respectively, compared with CK. The soil readily available water, soil delayed available water, and soil available water first increased and then decreased with the increase in nitrogen from straw instead of nitrogen from chemical fertilizer.

Soil equivalent pore

Compared with CK, S_{50} slightly increased soil capillary porosity, whereas S_{25} , S_{75} , and S_{100} increased it by 7.35%, 35.49%, and 39.70%, respectively, in 2018 (Fig. 8). S_{100} increased soil capillary porosity by 30.13% and 38.06%, whereas S_{75} increased it by 26.21% and 33.9% compared with S_{25} and S_{50} , respectively, in 2018. Soil capillary porosity with S_{25} was 6.09% higher than that with S_{50} in 2018.

S_{100} slightly decreased soil capillary porosity, whereas S_{50} decreased it by 25.00% relative to CK in 2019. S_{25} and S_{75} increased soil capillary porosity by 15.23% and 13.69%; by 53.64% and 51.59%; and by 17.29% and 15.72% compared with CK, S_{50} , and S_{100} , respectively, in 2019. Soil capillary porosity with S_{100} was 31.00% higher than that with S_{50} in 2019.

S_{25} slightly increased soil capillary porosity compared with CK, whereas S_{50} and S_{75} increased it by 25.39% and 27.14%; by 23.73% and 25.46%; and by 8.65% and 10.17% relative to CK, S_{25} , and S_{100} , respectively, in 2020. Soil capillary porosity with S_{100} was 15.41% and 13.88% higher than that with CK and S_{50} , respectively, in 2020.

S_{50} slightly decreased soil available water porosity compared with CK, whereas S_{25} , S_{75} , and S_{100} increased it by 5.73%, 26.81%, and 31.53%, and by 8.52%, 30.15%, and 34.99% compared with CK and S_{50} , respectively, in 2018. S_{75} and S_{100} increased soil available water porosity by 19.94% and 24.40%, respectively, relative to S_{25} in 2018 (Fig. 9). Soil available water porosity with S_{25} was 8.52% higher than that with S_{50} in 2018.

S_{100} slightly decreased soil available water porosity, whereas S_{50} decreased it by 23.30% relative to CK in 2019. S_{25} and S_{75} increased soil available water porosity by 15.06% and 11.03%; by 50.01% and 44.76%; and by 17.12% and 13.01% compared with CK, S_{50} , and S_{100} , respectively, in 2019. Soil available water porosity with S_{100} was 28.09% higher than that with S_{50} in 2019.

S_{25} slightly increased soil available water porosity compared with CK, whereas S_{50} and S_{75} increased it by 19.36% and 21.74%; by 16.72% and 19.05%; and by 7.21% and 9.35% compared with CK, S_{25} , and S_{100} , respectively, in 2020. Soil available water porosity with S_{100} was 11.33% and 8.87% higher than that with CK and S_{25} , respectively, in 2020.

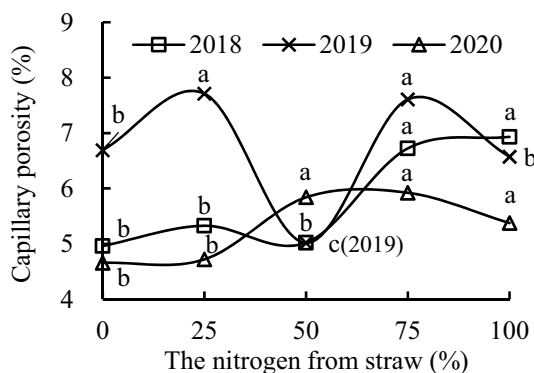


Figure 8. Capillary porosity of soil as a function of the different replacement treatments in 2018–2020.

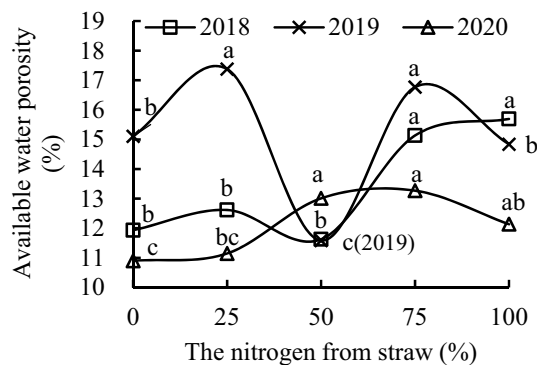


Figure 9. Available water porosity of soil as a function of the different replacement treatments in 2018–2020.

Principal component analysis

The values of soil water constant, soil available water content, and soil equivalent pore size reflect soil water-holding capacity and soil water supply capacity. To comprehensively measure the indices of soil water constant, soil available water content, and soil equivalent pore size, principal component analysis (PCA) was performed with the evaluation variables of soil specific water capacity (X_1), field capacity (X_2), wilting point (X_3), soil readily available water content (X_4), soil delayed available water content (X_5), soil available water content (X_6), soil capillary porosity (X_7), and soil available water porosity (X_8). Principal components (PCs) were extracted according to the criteria of characteristic values greater than 1 (Table 2). The first two PCs had a cumulative contribution rate of 99.97%. Thus, the original eight indices could be replaced by the two PCs for comprehensive evaluation. The PC1 contribution rate reached 80.08%, which mainly reflected the influence of soil specific water capacity (X_1), soil readily available water content (X_4), soil delayed available water content (X_5), soil available water content (X_6), soil capillary porosity (X_7), and soil available water porosity (X_8). The PC2 contribution rate reached 19.88%, which mainly reflected the influence of field capacity (X_2) and wilting point (X_3) (Table 3). Thus, soil specific water capacity, soil readily available water, soil delayed available water, soil available water, soil capillary porosity, and soil available water porosity could better reflect soil water-holding capacity and soil water supply capacity compared with field capacity and wilting point.

Principal component	Eigenvalue	Variance contribution rate (%)	Cumulative variance contribution rate (%)
1	6.4066565	80.08	80.08
2	1.5906670	19.88	99.97
3	0.0026057	0.03	100.00
4	0.0000449	0	100.00
5	0.0000194	0	100.00
6	0.0000036	0	100.00
7	0.0000023	0	100.00
8	0.0000005	0	100.00

Table 2. Explanation of total variance across principal component analysis.

Indicator variable	Principal component	
	1	2
X_1	0.391	-0.116
X_2	0.288	0.543
X_3	0.136	0.744
X_4	0.392	-0.096
X_5	0.393	0.079
X_6	0.394	-0.065
X_7	0.370	-0.277
X_8	0.382	-0.204

Table 3. Component matrix of principal component.

According to principal component analysis based on three-year average data, S_{25} , S_{75} and S_{100} positively correlated with the first principal component (Fig. 10). CK and S_{50} negatively correlated with the first principal component. S_{75} and S_{100} had a close distance, both located in quadrant IV, belonging to the same category. S_{25} , CK and S_{50} were far apart, located in quadrants I, II, and III respectively, belonging to different categories.

Discussion

The soil water characteristic curve can reflect the water holding and releasing characteristics of different soils, and can also be used to understand some soil water constants and characteristic indexes. Therefore, it is an important tool for studying soil water movement, regulating and utilizing soil water, and soil improvement. Fan et al. (2020) Fan²⁶ reported that incorporating straw of rape, maize, potato, oats, and buckwheat increased field capacity compared with non-cultivated and without fertilization in the 0–60-cm soil layer. Ren²⁷ demonstrated that different straw returning depths enhanced field capacity compared with no fertilization. Du²⁸ showed that the wilting coefficient of finely cut straw was higher than long cut straw. In this study, S_{25} increased field capacity and wilting point from the fourth fertilization year, whereas the rest of the replacement treatments had lower field capacity and wilting point compared with CK. This might be because S_{25} had lower straw incorporation rate, which resulted in complete straw decomposition, whereas the rest of the replacement treatments had a higher straw incorporation rate, which resulted in incomplete straw decomposition. In addition, the replacement of mineral fertilization with straw might have immobilized soil inorganic N in the initial stages of maize. Meanwhile, because the decomposition degree of straw was affected by soil moisture, the nitrogen, phosphorus, potassium and other trace elements released during the decomposition of straw would affect the soil moisture and nutrient status and improve the water retention performance of the soil.

Yang²⁹ found that the returning of straw of rice, maize, and wheat significantly increased soil water retention capacity at the matric potential of -0.033 and -1.5 MPa, and consequently, enhanced soil available water content. Fan³⁰ reported that straw returning improved the effects of potassium fertilizer on soil porosity. This study showed that S_{50} decreased soil specific water capacity, soil readily available water, soil delayed available water, soil available water, and soil available water porosity in 2018 and 2019, whereas S_{50} increased these in 2020 compared with single application of mineral fertilizer. These indicated that S_{50} could increase soil water-holding capacity and soil water supply capacity over time. Because the crop root system is the absorption organ of soil moisture and nutrients, it can respond to soil moisture. It was speculated that the reason was that the effective nitrogen content in the soil was sufficient when the content of straw nitrogen and inorganic nitrogen was 50% respectively, which might increase the root density by stimulating the growth of maize roots near the nitrogen-rich area, thereby increase the hydraulic conductivity of maize and improve the absorption of soil moisture by maize. This study also presented that replacement treatments increased soil readily available water, soil delayed available water, soil available water, soil capillary porosity, and soil available water porosity relative to single application of mineral fertilizer in the fifth fertilization year. This might be because continuous straw incorporation promoted the formation of larger soil macroaggregates³¹, which resulted in the improvement of soil structure.

Soil organic carbon is an important chemical component in soil, which can characterize the change in soil quality. Studies had shown that different proportions of straw returning had different effects on the change of soil organic carbon content, but less or too much straw returning would hinder the decomposition of straw and slow down the increased rate of soil organic carbon³². At the same time, the application of nitrogen fertilizer could change the number of microbial populations in the soil, promote their activity, build a healthy soil micro-ecological environment, further promote the growth of crop roots, and strengthen the efficient use of water in

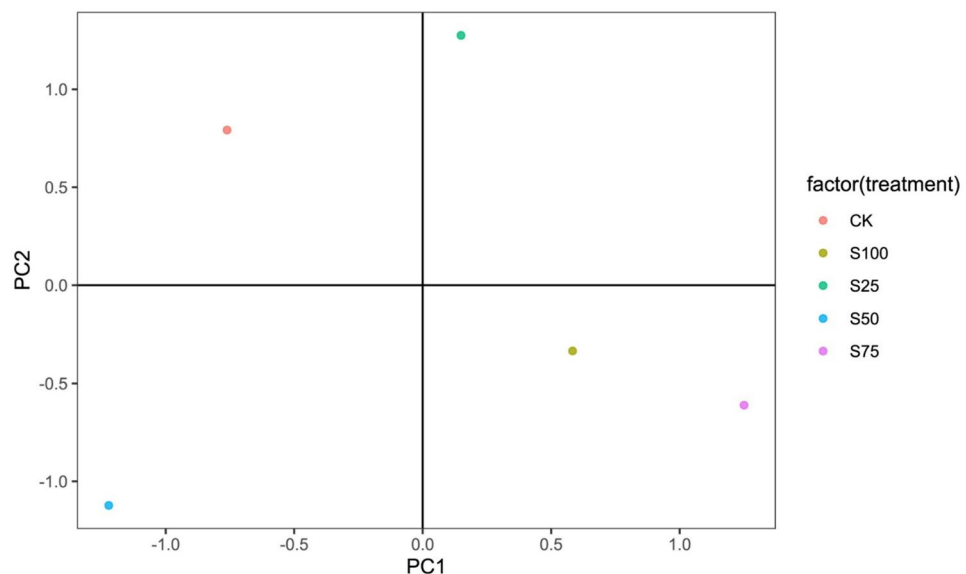


Figure 10. Principal component analysis based on three-year average data.

the soil by crops. Straw returning would also increase the content of soil organic carbon³³. Soil organic carbon is also the main precursor of soil humus and aggregates, which is of great significance in improving soil fertility. This shows that the application of appropriate straw nitrogen substitution for inorganic fertilizer may be to maintain soil moisture and nutrient characteristics by increasing the content of organic carbon in the soil. Besides, the results showed that soil specific water capacity, soil readily available water, soil delayed available water, soil available water, soil capillary porosity, and soil available water porosity could better reflect soil water-holding capacity and soil water supply capacity compared with field capacity and wilting point. It was indicated that in this experimental area when the straw was used to replace part of chemical fertilizer under the condition of equal nitrogen amount, more attention should be paid to the changes of soil specific water capacity, soil readily available water, soil delayed available water, soil available water, soil capillary porosity and soil available water porosity. Fertilization measures to increase soil specific water capacity, soil readily available water, soil delayed available water, soil available water, soil capillary porosity and soil available water porosity had a beneficial effect on improving soil water status and promoting soil health, thereby promoting crop growth. It could also be speculated that the appropriate adjustment of the proportion of straw nitrogen instead of chemical fertilizer nitrogen according to rainfall conditions would help to better play the benefits of straw returning to the field, promote the water and nitrogen cycle of agricultural ecosystems, and maintain ecological balance.

The significance of replacing part of mineral nitrogen with organic nitrogen in straw is also to reduce the application of mineral nitrogen without damaging the nutritional status of the plant. In this experiment, the effects of straw organic nitrogen instead of mineral nitrogen on soil moisture characteristics in different experimental years were mainly explored. Efficient use of water is one of the important conditions to ensure the normal growth and development of crops. Under the condition of equal nitrogen amount of straw instead of chemical fertilizer application, it can not only ensure the normal metabolic activity in the process of crop vegetative growth and reproductive growth, but also promote the improvement of soil physical and chemical properties, and finally achieve the effect of saving chemical fertilizer and reducing environmental pollution, which is the focus of this experimental study in the future.

Conclusions

Replacing nitrogen from mineral fertilizer with nitrogen from maize straw gradually increased soil water-holding capacity and soil water supply capacity relative to applying mineral fertilizer only over time. The 25% nitrogen provided by maize straw combined with the 75% nitrogen provided by mineral fertilizer increased field capacity and wilting point compared with applying mineral fertilizer only at the same nitrogen content. Applying equal proportions of nitrogen from maize straw and mineral fertilizer increased soil water availability and soil available water porosity relative to applying mineral fertilizer only from the fifth fertilization year.

Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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References

- Zhang, X. *et al.* Managing nitrogen for sustainable development. *Nature*. **528**, 51–59 (2015).
- Zeng, J. *et al.* Nitrogen fertilization directly affects soil bacterial diversity and indirectly affects bacterial community composition. *Soil Biol. Biochem.* **92**, 41–49 (2016).
- Bai, H. *et al.* Influences of irrigation amount on the rhizospheric microorganism composition and carbon dioxide flux of maize crops. *Geoderma* **343**, 1–9 (2019).
- Azeem, B., KuShaari, K., Man, Z. B., Basit, A. & Thanh, T. H. Review on materials & methods to produce controlled release coated urea fertilizer. *J. Control. Release* **181**, 11–21 (2014).
- Bouraima, A., He, B. & Tian, T. Runoff, nitrogen (N) and phosphorus (P) losses from purple slope cropland soil under rating fertilization in three gorges region. *Environ. Sci. Pollut. Res.* **23**, 4541–4550 (2016).
- Mohamed, I. *et al.* Rice straw application with different water regimes stimulate enzymes activity and improve aggregates and their organic carbon contents in a paddy soil. *Chemosphere* **274**, 129971 (2021).
- Rahman, M. T., Liu, S., Guo, Z. C., Zhang, Z. B. & Peng, X. H. Impacts of residue quality and N input on aggregate turnover using the combined ¹³C natural abundance and rare earth oxides as tracers. *Soil Till Res.* **189**, 110–122 (2019).
- Sharma, S., Singh, P., Choudhary, O. P. & Neemisha. Nitrogen and rice straw incorporation impact nitrogen use efficiency, soil nitrogen pools and enzyme activity in rice-wheat system in North-Western India. *Field Crops Res.* **266**, 108131 (2021).
- Singh, S. & Sharma, S. Temporal changes in rhizosphere biological soil quality indicators of wheat in response to nitrogen and straw incorporation. *Trop. Ecol.* **61**, 328–344 (2020).
- Li, T. *et al.* Influence of Green Manure and rice straw management on soil organic carbon, enzyme activities, and rice yield in Red Paddy Soil. *Soil Till Res.* **195**, 104428 (2019).
- Celik, I., Gunal, H., Budak, M. & Akpınar, C. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid mediterranean soil conditions. *Geoderma* **160**, 236–243 (2010).
- Raza, S. *et al.* Dramatic loss of inorganic carbon by nitrogen-induced soil acidification in Chinese Croplands. *Glob. Change Biol.* **26**, 3738–3751 (2020).
- Li, P. *et al.* Crop yield-soil quality balance in double cropping in china's upland by organic amendments: A meta-analysis. *Geoderma* **403**, 115197 (2021).
- Seiz, P., Guzman-Bustamante, I., Schulz, R., Müller, T. & Ruser, R. Effect of crop residue removal and straw addition on nitrous oxide emissions from a horticulturally used soil in South Germany. *Soil Sci. Soc. Am. J.* **83**, 1399–1409 (2019).
- Wang, Y. *et al.* Does continuous straw returning keep China farmland soil organic carbon continued increase? A Meta-Analysis. *J. Environ. Manag.* **288**, 112391 (2021).
- Pang, D. *et al.* Effect of returning methods of maize straw and nitrogen treatments on soil physicochemical property and yield of winter wheat. *Acta Agronomica Sinica* **42**, 1689–1699 (2016).

17. Li, L., Wang, J., Zhu, Z. M., Fan, L. Q. & Wu, X. Effects of nitrogen fertilizer reduction combined with organic fertilizer/straw on soil fertility index and maize yield in saline-alkali land. *Chin. J. Soil Sci.* **51**, 928–935 (2020).
18. Liu, S. S., Zheng, X. Q., Chen, J. F. & Wu, B. Effect of irrigation and nitrogen treatments on nitrogen migration and accumulation in soil phase transition during freezing-thawing period. *Agric. Res. Arid Areas.* **35**, 166–172 (2017).
19. Huang, C. *Soil Science* (China Agriculture Press, 2005).
20. Leij, F. J., Russell, W. B. & Lesch, S. M. Closed-form expressions for water retention and conductivity data. *Ground Water.* **35**, 848–858 (1997).
21. Ning, T., Guo, Z. S. & Li, Y. L. Soil water characteristic curves and soil water constants at different depths in the abandoned sloping filed of loess hilly region. *J. Soil Water Conserv.* **28**, 166–170 (2014).
22. Zhang, L., Han, J. C., Luo, L. T., Ma, Z. H. & Wang, H. Y. Water-holding characteristics of compounded soil with feldspathic sandstone and aeolian sandy soil. *J. Northwest Sci.-Tech. Univ. Agric. For. (Nat. Sci. Ed.)* **42**, 207–214 (2014).
23. Duncan, D. Multiple range and multiple f tests. *Biometrics* **11**, 1–42 (1955).
24. Ma, C. C., Wang, F., Mu, X. M. & Kang, S. Z. Effect of the mechanical action of wheat roots on soil water characteristic curve. *J. Soil Water Conserv.* **27**, 105–109 (2013).
25. Zhuang, J. P. & Wang, W. Studies on the relationship between soil water-retention characters in low suction range and the early stage of soil drought. *Acta Pedologica Sinica* **23**, 306–313 (1986).
26. Fan, Q. Y. *et al.* Effect of different crop straw mulching on alluvial soil structure improvement. *J. Soil Water Conserv.* **34**, 230–236 (2020).
27. Ren, X. *et al.* Effects of Straw returning depth on nutrients and physical properties of Yellow Brown Soil. *Bull. Soil Water Conserv.* **38**, 58–64 (2018).
28. Du, X. *The Effect of Crushed Straw Dosage on the Main Physical and Chemical Properties of Soil and Crop Growth* 47–48 (Northwest A&F University, 2011).
29. Yang, C. D. & Lu, S. G. Effects of five different biochars on aggregation, water retention and mechanical properties of paddy soil: A field experiment of three-season crops. *Soil Till Res.* **205**, 104798 (2021).
30. Fan, Y. *et al.* Effects of straw returning and potassium fertilizer application on root characteristics and yield of spring maize in China Inner Mongolia. *Agron. J.* **113**, 4369–4385 (2021).
31. Wang, Z. *et al.* Combined effects of nitrogen fertilizer and straw application on aggregate distribution and aggregate-associated organic carbon stability in an alkaline sandy loam soil. *Eur. J. Soil Sci.* **69**, 1105–1116 (2018).
32. Wang, Y. *et al.* Does continuous straw returning keep China farmland soil organic carbon continued increase? A meta-analysis. *J. Environ. Manage.* **288**, 112391 (2021).
33. Pimentel, M. L. *et al.* Quantity, quality and physical protection of soil carbon associated with sugarcane straw removal in Southern Brazil. *Soil Till Res.* **237**, 105976 (2024).

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Author contributions

All authors read and approved the final manuscript. X.W.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing. L.T.: Writing—review & editing. T.W.: Collect data. E.Z.: Take soil samples in 2020.

Competing interests

The authors declare no competing interests.

Additional information

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