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N Fertilizer in Combination with Straw Improves Soil Physicochemical Properties and Crop Productivity in Sub-Humid, Drought-Prone Areas

Qingyue Liu [1], Liang Lu [2,3], Jian Hou [2,3], Jinling Bai [2,3], Qin'ge Dong [1,2,3,*], Hao Feng [2,3], Yufeng Zou [2,3,*] and Kadambot H. M. Siddique [4]

[1] College of Water Resources and Architectural Engineering, Northwest A&F University, Xianyang 712100, China; liuqingyue_mp@nwafu.edu.cn
[2] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Northwest A&F University, Xianyang 712100, China; lluliang@nwafu.edu.cn (L.L.); 2023055919@nwafu.edu.cn (J.H.); 2023050971@nwafu.edu.cn (J.B.); fenghao@nwafu.edu.cn (H.F.)
[3] Institute of Soil and Water Conservation, Northwest A&F University, Xianyang 712100, China
[4] The UWA Institute of Agriculture and School of Agriculture and Environment, The University of Western Australia, LB 5005, Perth, WA 6001, Australia; kadambot.siddique@uwa.edu.au
* Correspondence: qgdong2014@nwafu.edu.cn (Q.D.); zouyufeng@nwafu.edu.cn (Y.Z.); Tel.: +86-29-87012465 (Q.D.); +86-15339264685 (Y.Z.)

Abstract: Straw returning may be an efficient strategy to maintain agricultural sustainability. However, which straw returning strategy can effectively improve soil properties and crop yield remain unclear. A five-year (2011–2016) field experiment in sub-humid, drought-prone areas of northwestern China with uneven rainfall distribution and irrigation was conducted to evaluate the effects of nitrogen fertilizer without straw mulching (CK), with regular straw mulching (LSM), and with ammoniated straw plowing (ALSP) on soil water, soil aggregates, soil organic carbon (SOC), total nitrogen (TN), and water use efficiency (WUE) in an annual winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.) rotation system. The results demonstrate that ALSP had a greater soil water content than CK in the 0–60 cm soil layer. ALSP also had substantially more soil water than LSM in the 0–100 cm layer during the wet year (2011–2012) and two dry years (2014–2015 and 2015–2016). In the normal years (2012–2013 and 2013–2014), the soil water content in ALSP was significantly lower than in LSM in the 0–20 cm soil layer. ALSP was better able to alleviate soil drought in dry years and excessive humidity in wet years. Compared to CK, SOC in the 0–20 cm soil layer in 2016 increased by 8.3% in LSM and 11.7% in ALSP, and TN in the upper soil increased by 6.6% in LSM and 10.1% in ALSP. The equivalent wheat yield and WUE increased in ALSP by 15.6% and 17.5%, respectively, relative to CK, and by 6.79% and 5.97%, respectively, relative to LSM. Thus, we concluded that plowing ammoniated straw with N fertilization is a promising strategy for improving soil fertility and crop productivity in winter wheat–summer maize rotation systems in the sub-humid, drought-prone areas of northwestern China.

Keywords: ammoniated straw incorporation; soil water; soil organic carbon; total nitrogen; uneven rainfall

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1. Introduction

Soil moisture and fertility are the key factors limiting agricultural productivity [1]. To meet the needs of the growing population and ensure food security, large quantities of mineral nitrogen fertilizer (N) are applied to soils in northwestern China to improve soil fertility, water utilization, and crop production efficiency [2]. However, the improvements in crop yield come at the cost of greater environmental burdens, such as the deterioration of soil quality, decreased in water infiltration depth with higher fertilization, and agricultural environment problems [3]. The southern Loess Plateau of northwestern China

is a vast semi-humid, drought-prone area receiving 400–600 mm of annual rainfall that is unevenly distributed (60–70% falls from July to September) and has high rates of soil water evaporation [4]. The winter wheat–summer maize rotation system has been widely adopted in this region. Like other dry regions of the world, water scarcity and declining soil fertility are critical ecological factors limiting agricultural productivity. In 1961–2014, the annual precipitation in this region declined at an average rate of 0.751 mm per year [5]. Excessive N fertilization and reduced organic matter input have negatively affected soil physicochemical properties and crop yields [6]. Therefore, the conventional management practices used are unlikely to be sustainable. Thus, alternative field management practices are essential for cropping systems in sub-humid, drought-prone areas of northwestern China and other water- and fertility-limited regions of the world, such as West Africa [7], Argentina [8], and India [1].

Returning crop straw to fields is an effective practice for developing sustainable agriculture in arid and semi-arid areas [3]. Applying crop straw increases soil organic carbon (SOC) inputs, improves soil physicochemical and biological properties, and increases crop yields and water use efficiency (WUE) [9,10]. However, straw returning alone may not be sufficient to maintain current crop production levels due to its limited availability and low nutrient content. Combining mineral fertilization with crop straw incorporation can improve crop yields and SOC [10]. Gentile et al. reported that combining chemical fertilizers with crop straw could match the rate of soil N supply with plant N uptake, improve system N use efficiency, and reduce N losses through leaching beyond the crop rooting depth [11]. Thus, integrating crop straw and chemical fertilizers is a rational strategy to improve soil nutrient levels and promote crop growth in intensive agriculture [12]. There are many strategies for applying straw, including long straw mulching, long straw ammonification and plowing, crushed straw ammonification and plowing, long straw ammonification + calcium sulfate plowing, crushed straw ammonification + calcium sulfate plowing, and so on [13].

Currently, this integrated strategy includes two main types: (1) straw mulching combined with N fertilizer and (2) straw incorporation (plowed into the soil) combined with N fertilizer. Straw mulching can decrease soil compaction, reduce erosion, increase rainfall storage as soil water by increasing infiltration, and reduce water loss by evaporation [14]. Straw mulching combined with N fertilizer can increase SOC, improve soil aggregation, promote biological activity, and enhance crop yield and WUE [2]. However, low soil temperatures caused by straw mulching could freeze wheat seedlings and roots during winter, negatively affecting seed germination, tillering, and crop yields in arid and semi-arid areas [15]. Straw mulching can also reduce soil moisture by intercepting precipitation during frequent but small rainfall. Comparatively, straw incorporation may more effectively improve soil organic matter, enhance soil aggregate stability [16], and increase nutrient use efficiency. For example, Memon et al. have reported that reduced tillage with 60% straw incorporation may increase soil TN concentration by 0.98 g/kg, soil organic matter (SOM) by 17.07%, and soil carbon storage (SCS) by 14.20% more than other treatments [17]. Additionally, soil microorganisms and plants may compete for the same N source during straw decomposition, resulting in N starvation for the crop and reduced crop yields [18]. An incorporation of crop straw with a high C/N ratio can increase the net immobilization of N, reducing the amount of available N for nitrification and denitrification [11]. Straw incorporation combined with N fertilizer can reduce soil bulk density, improves soil water-holding capacity, increases SOC, enhances fertilizer efficiency, and increases crop yield under soil moisture stress [5]. Yu et al. and Li et al. reported that the incorporation of ammoniated straw with a low C/N ratio (approximately 25:1) and nitrogen fertilization modified the straw lignin characteristics; significantly decreased lignin, hemicellulose, and cellulose contents; increased crude protein content to improve nutrient release from the straw; damaged the ester compounds on the outer layer of the stratum corneum [19]; accelerated straw decomposition; and increased crop productivity in semi-arid areas [20,21]. However, some studies showed that the incorporation of crop

straw with N fertilizer may not increase SOC sequestration [22], decrease the formation of macroaggregates > 0.2 mm [23], or negatively influenced the early growth or yields of crops, such as wheat, sugar beet (*Beta vulgaris* L.), oilseed rape (*Brassica napus* L.) and rice (*Oryza sativa* L.), due to water-soluble toxins (e.g., phenolic acids) during straw decomposition [24]. Although many studies have investigated the effects of straw mulching or incorporation combined with N fertilizer on improving SOC and increasing crop yield and WUE in crop–fallow systems (i.e., wheat or maize followed by fallow) in arid and semi-arid areas [3], and in humid areas [11], the results are controversial and little is known for crops in sub-humid drought-prone areas.

Winter wheat–summer maize rotation systems in sub-humid drought-prone areas of northwestern China have received little attention. These areas have similar climatic features to semi-arid areas and experience drought stress during the cropping season (especially winter and spring), reducing crop productivity [4]. While some studies have reported the effects of straw mulching on soil N dynamics and crop productivity in this region [2,4], little is known about the long-term effects of ammoniated straw incorporation with N fertilization on soil properties and crop productivity in a winter wheat–summer maize cropping system. Meanwhile, a systematic and quantitative assessment of the differences between straw mulching and ammoniated straw incorporation with N fertilization on soil properties and crop yield components has not been conducted for the winter wheat–summer maize rotation system in sub-humid, drought-prone areas of northwestern China.

We hypothesized that integrating N fertilizer and crop straw in a winter wheat–summer maize rotation system would significantly enhance soil aggregation, improve SOC and TN, increase soil water utilization (rainfall and irrigation), and boost crop productivity through the efficiently using of rainfall and improving soil properties. The objectives of this study were to examine the effects of different straw returning strategies (N fertilizer plowed into the soil and straw mulching, and ammoniated straw with N fertilizer plowed into the soil) on the soil physicochemical properties and crop productivity under irrigated conditions with uneven rainfall distribution to optimize straw application in winter wheat–summer maize rotation systems in the sub-humid, drought-prone areas of northwestern China.

2. Materials and Methods

2.1. Experimental Site

Field experiments were conducted during the growing seasons of 2011−2016 at the irrigation experimental station of the Key Laboratory of Agricultural Soil and Water Engineering sponsored by the Ministry of Education (34°18′ N, 108°04′ E, 506 m asl) in Yangling, Shaanxi, China (Figure 1). Based on the long-term weather data measured by the meteorological station in the irrigation experimental station, this region has a northern subtropical monsoon climate with an average annual air temperature of 13 °C and rainfall of 638 mm, with nearly 60% falling between July and September. The rainfall distribution and air temperature were recorded throughout the experiment. The soil at the site was a silt clay loam, with a mean bulk density of 1.45 g cm^{-3} and 0.95 g kg^{-1} total nitrogen in the root zone soil (Table 1).

Table 1. Physical and chemical characteristics of the 0–100 cm soil layer before the experiment in 2011.

Sand (%)	Silt (%)	Clay (%)	BD (g cm^{-3})	SOC (g kg^{-1})	TN (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	pH
8.3	73.6	18.1	1.45	9.94	0.95	5.19	1.31	12.28	174.6	8.4

Notes: BD indicates soil bulk density. SOC indicates soil organic carbon. TN indicates soil total nitrogen.

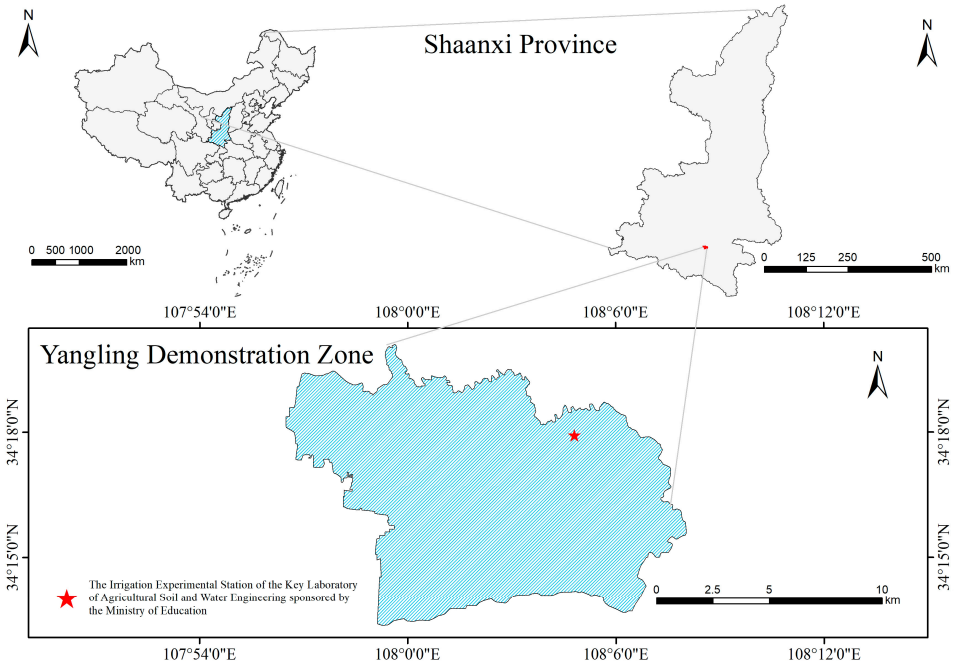


Figure 1. Location of experimental site.

2.2. Experimental Design

The experimental field had been cultivated with a winter wheat and summer maize rotation system for 20 years prior to establishing the experiment. The experiment utilized the winter wheat straw and summer maize straw produced by rotation in the experimental field. This experiment had three treatments: (i) conventional tillage with N fertilizer plowed into the soil and no straw mulching (CK), (ii) conventional tillage with N fertilizer plowed into the soil and regular straw (5 cm long) mulching (LSM), and (iii) conventional tillage with ammoniated straw with N fertilizer plowed into the soil (ALSP). The CK treatment consisted a flat, non-mulched plot. The three treatments were arranged in a randomized complete block design with three replications, and each plot was 5 m long and 4 m wide.

The CK treatment received 225 kg N ha^{-1} as $CO(NH_2)_2$ and 90 kg P ha^{-1} as $Ca(H_2PO_4)_2$ evenly broadcast before summer maize planting, and 150 kg N ha^{-1} as $CO(NH_2)_2$ and 100 kg P ha^{-1} as Ca $(H_2PO_4)_2$ evenly broadcast before winter wheat planting. The LSM treatment received 225 kg N ha^{-1} as $CO(NH_2)_2$ and 90 kg P ha^{-1} as $Ca(H_2PO_4)_2$ evenly broadcast before summer maize planting, and 150 kg N ha^{-1} as $CO(NH_2)_2$ and 100 kg P ha^{-1} as Ca $(H_2PO_4)_2$ evenly broadcast before winter wheat planting. In the LSM treatment, wheat straw (4.0 t ha^{-1}) was applied to the maize plot, and maize straw (4.0 t ha^{-1}) was applied to the wheat plot after sowing. The ALSP treatment received 173 kg N ha^{-1} and 90 kg P ha^{-1} evenly broadcast before sowing summer maize, 98 kg N ha^{-1} and 100 kg P ha^{-1} evenly broadcast before sowing winter wheat, and the remaining 52 kg N ha^{-1} was used to ammoniate 4.0 t of maize or wheat straw, which was plowed into the soil before each sowing (Table 2). Ammoniated straw is a type of straw that has been processed through specific techniques to improve its digestibility and nutritional value. The ammoniated straw was prepared as follows: (1) 112 kg urea (52 kg N) was dissolved in 2.0 t of water to create an aqueous solution; (2) the solution was evenly sprayed on 4.0 t crop straw to achieve a straw C/N ratio of approximately 25/1; and (3) the crop straw was mixed and sealed in airtight plastic bags that were placed for 5 days at room temperature (26 °C). Through an ammonolysis reaction, while breaking the ester bonds between lignin and polysaccharides, ammonium salts are formed to provide a source of nitrogen fertilizer for the soil. All fertilizers were plowed into the topsoil (0–20 cm) using rotary tillage before sowing.

Table 2. Treatment setting table of the field experiment.

Treatment	Crop	N (kg kg^{-1})	P (kg ha^{-1})	Straw (t ha^{-1})
CK	maize	225	90	0
	wheat	150	100	0
LSM	maize	225	90	4
	wheat	150	100	4
ALSP	maize	173 52 (use to ammoniate straw)	90	4
	wheat	98 52 (use to ammoniate straw)	100	4

Maize seeds (cv. Qinlong-11) were sown at a density of 50,000 plants ha^{-1} between 9 June and 20 June and harvested between 1 October and 12 October each year. The maize had uniform row spacing with wide row (60 cm) and narrow row (30 cm). Each plot received 80 mm of irrigation in the 2013 growing season but not in the other growing seasons (Table 3). Wheat seeds (cv. Xiaoyan-22) were planted at a seeding rate of 150 kg ha^{-1} between 16 October and 19 October and harvested between 5 June and 8 June each year. Winter wheat was planted in rows 25 cm apart. Each plot received 180 mm of irrigation in 2011–2012, 120 mm in 2012–2013, and 60 mm in 2013–2014 and 2014–2015 seasons due to drought stress, but none in 2015–2016 (Table 3).

Table 3. Rainfall and irrigation in the 2011–2016 summer maize–winter wheat rotation seasons.

Crop	Growing Season	Year	Rainfall (mm)	Irrigation (mm)
Maize	June–October	2011	616.5	0
		2012	432.5	0
		2013	224.1	80
		2014	379.6	0
		2015	283.2	0
Wheat	October–June	2011–2012	192.3	180
		2012–2013	223.7	120
		2013–2014	298.2	60
		2014–2015	239.4	60
		2015–2016	203.3	0

2.3. Soil Sampling and Analysis Methods

2.3.1. Soil Properties

Soil samples were collected at the depths of 0–10 and 10–20 cm during wheat harvest in 2011, 2013, 2014, and 2016 and during the maize harvest in 2013 and 2015. Soil sampling was carried out using a soil drill, with three replications for each treatment in the collected samples. All fresh samples were divided into two portions. One portion of soil samples, collected from five points in each plot during wheat harvest in 2013 and 2016, was immediately transported to the laboratory and air-dried to determine soil water-stable aggregates (WSAs) using the wet-sieving procedure described by Oades and Waters et al. A total of 100 g of 5 to 8 mm aggregates was placed on top of a set of sieves with 5, 2, 1, 0.5, and 0.25 mm mesh diameters, saturated for 30 min, and oscillated in a water column for 3 min. The soil retained on each sieve was oven-dried at 50 °C and weighed to calculate the percentage of WSA. The other portion of soil samples from each plot was collected from five points and mixed to produce a composite sample. These soil samples were air-dried and sieved through a 0.25 mm screen to determine SOC and TN using the dichromate oxidation method and Kjeldahl method, respectively.

2.3.2. Crop Evapotranspiration (ET_a)

During each summer maize or winter wheat growing season, the gravimetric soil water content was measured every two weeks at 20 cm intervals within the 0–100 cm profile. The soil water storage (*SWS*) within the 0–100 cm soil layer in each plot was considered as the total water storage as follows:

$$SWS = \sum SWC_i \times h_i \quad (1)$$

where *SWC* is the soil water content of soil layer *I* (vol.%) and h_i is the depth of the soil layer (mm).

In each experimental season, the actual evapotranspiration (ET_a) was calculated from the soil water balance equation:

$$ET_a = I + P_e - R - Q - \Delta SWS \quad (2)$$

where *I* is the irrigation depth (mm), P_e is the effective rainfall (mm), *R* is the runoff loss from the ground surface (mm), *Q* is the vertical soil water exchange at a depth of 100 cm (mm; positive downward, negative upward), and ΔSWS is the difference in soil water storage in the 100 cm soil layer between the two soil water measurements at the beginning and end of the season (mm). The groundwater table remained about 50 m below the surface, and irrigation and rainfall were low; so, the upward and downward water flow into the roots was negligible, except in the 2011 summer maize season due to extremely heavy rainfall. The surface runoff was omitted due to the deep groundwater table and the experimental field being relatively flat.

2.4. Yield Measurements

Prior to the harvest of summer maize or winter wheat each year, the number of spikes per unit area was recorded for each treatment. Grain yields were measured by hand-harvesting two adjacent center rows (90 cm wide and 500 cm long) for summer maize and four rows (100 cm wide and 100 cm long) for winter wheat in each plot at maturity. The harvest samples were sun-dried for 6–10 days and weighed after threshing. Grain yields of winter wheat and summer maize were calculated when the water content in the sun-dried grain was approximately 13% (measured by the oven-drying method). The yield of each treatment was calculated as the mean value of three replications. At harvest, 20 maize and 100 wheat plants were selected in each plot to measure harvest factors, including kernel number per spike, kernel mass, aboveground biomass, and grain weight.

The water use efficiency (*WUE*) was calculated as:

$$WUE = Y/ET_o \quad (3)$$

where *Y* is the grain yield (kg ha^{-1}) and ET_o is the actual crop evapotranspiration (mm).

The total crop productivity for each treatment was calculated using the equivalent wheat yield (*EWY*) of the crops and their respective minimum support price (MSP) fixed by the government for the unit quantity of the respective grains during the corresponding harvest season.

$$EWY \text{ (kg ha}^{-1}\text{)} = \text{winter wheat yield} + (\text{summer maize yield} \times \text{MSP of summer maize})/\text{MSP of winter wheat} \quad (4)$$

2.5. Statistical Analysis

Experimental data were submitted for an analysis of variance (ANOVA) using the SPSS 26.0 statistical package. Multiple comparisons of crop yields, WUE, and related harvest factors were performed using the least significant difference (LSD) at the 0.05 level.

3. Results

3.1. Climatic Features

The monthly mean maximum and minimum temperatures followed a similar distribution trend each season, decreasing from June of the first year to January of the second year and increasing from January to May in the second year (Figure 2). The monthly rainfall presented different distribution characteristics each year. Rainfall from June to September accounted for more than 60% of the annual rainfall each year, except in 2013–2014 (Figure 2 and Table 3). The 2011–2012 and 2012–2013 growing seasons had 38.1% and 12.1% more rainfall, respectively, than the 62-year mean rainfall, while 2013–2014 and 2015–2016 had 10.8% and 16.9% less rainfall, respectively, than the 62-year mean (Figure 2 and Table 3).

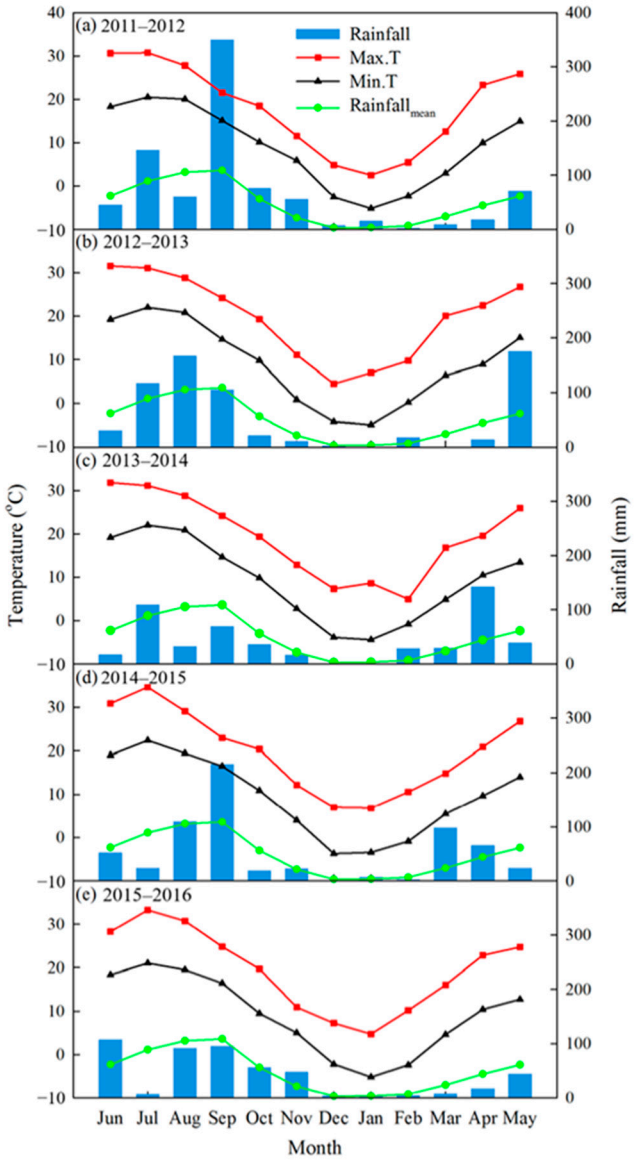


Figure 2. Monthly mean maximum temperature, minimum temperature, and rainfall distribution during the 2011–2016 growing seasons for summer maize and winter wheat at the experimental site. Max. T indicates maximum air temperature. Min. T indicates minimum air temperature. Rainfall$_{mean}$ indicates long-time mean rainfall from 1955 to 2016.

3.2. Soil Water and ET_a

Soil water content dynamics in the 0−100 cm layer differed between the five growing seasons (Figure 3a). The inter-annual variation in the soil water content in different growing

seasons depended greatly on rainfall, management practices, and crop water uptake. The experimental area has less precipitation in winter and spring (winter wheat growth period), and different straw returning measures have a more significant impact on the soil moisture content. The summer corn growth period has more abundant rainfall, and the impact of different measures on moisture is not significant. For summer maize, the 2013 and 2015 growing seasons had less soil water content than the other growing seasons as less rainfall occurred between July and September. In the winter wheat growing seasons, the soil water content differed due to different rainfall amounts and crop water uptake.

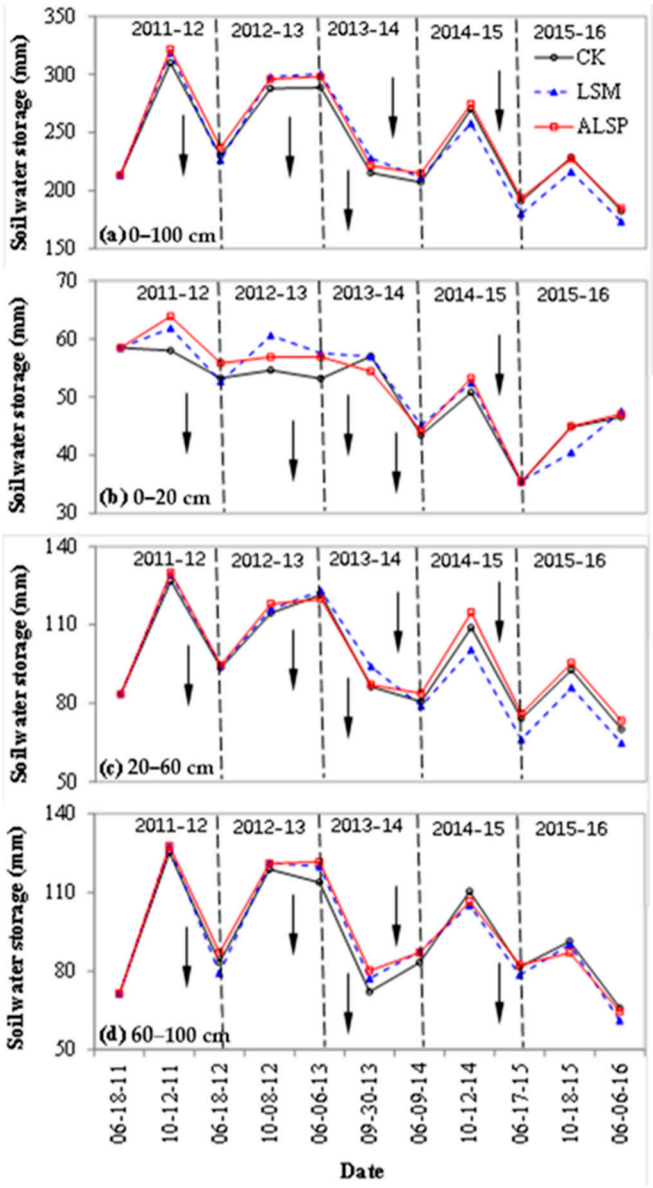


Figure 3. Soil water storage (it was an average) in the 0–100 cm, 0–20 cm, 20–60 cm, and 60–100 cm soil layers of CK, LSM, and ALSP during five summer maize–winter wheat rotation seasons. Standard deviation not plotted to simplify presentation. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. The solid, black arrows indicate that irrigation was applied.

The soil water content in the 0–100 cm soil layer declined over the growing seasons in the order of ALSP > LSM > CK in all years, except 2014–2016 (ALSP > CK > LSM) and 2013–2014 (LSM > ALSP > CK) (Figure 3a). LSM and ALSP had 2.8% and 3.3% more soil water, respectively, than CK in the 0–100 cm soil layer until the winter wheat harvest in 2013–2014. At 0–20 cm, LSM and ALSP had more soil water than CK for the duration of the experiment (Figure 3b); ALSP significantly increased 16.24% of soil water content, relative to the increment in LSM; specifically, ALSP > LSM in 2011–2012 and 2014–2016, and ALSP < LSM in 2012–2014. Similarly, at 20–60 cm, LSM and ALSP had more soil water than CK for the duration of the experiment, except for LSM in 2014–2016 (Figure 3c), and ALSP had 2.4% more soil water than CK across the five years (Figure 3c). At 60−100 cm, LSM and ALSP had 2.7% and 4.7% more soil water, respectively, than CK until the winter wheat harvest in 2013–2014, after which they had 4.4% and 2.5% less soil water, respectively (Figure 3d).

During the summer maize growing seasons, rainfall plus irrigation ranged from 283.2 to 616.5 mm, and ET_a ranged from 245.4 to 384.3 mm (Figures 2a and 4a). The ET_a between treatments differed in each summer maize growing season, except for 2015. During the winter wheat growing seasons, rainfall plus irrigation ranged from 203.3 to 372.3 mm, and ET_a ranged from 245.1 to 399.2 mm (Figures 2b and 4b). The ET_a between treatments differed in the 2011–2012 and 2012–2013 winter wheat growing seasons. In addition, 2013–2014 had the highest ET_a, due to the higher amount of rainfall plus irrigation, while 2015–2016 had the lowest—accounting for 65.2% in 2013–2014—indicating that rainfall plus irrigation significantly affected the actual evapotranspiration.

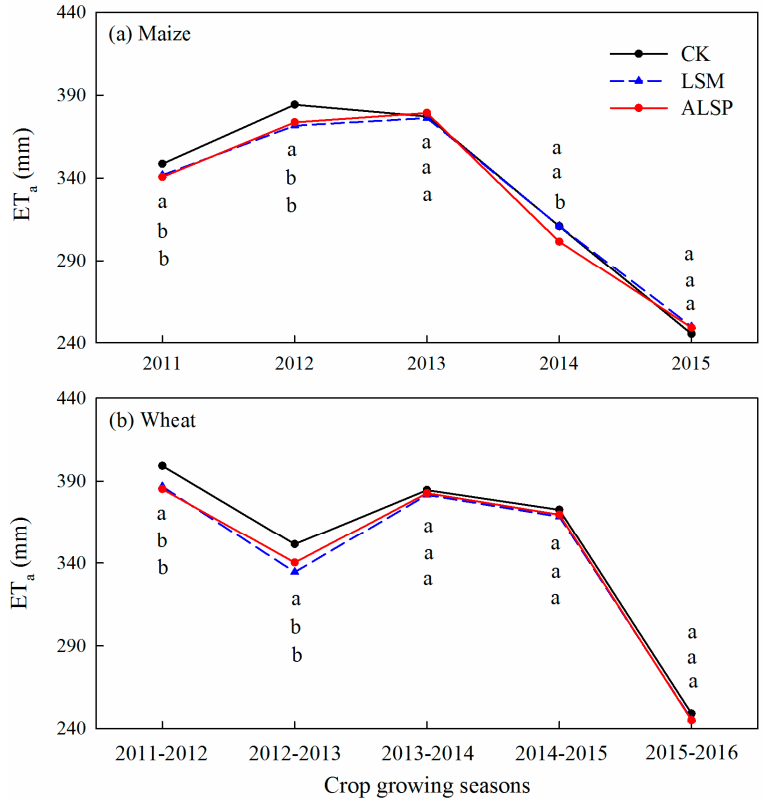


Figure 4. Actual evapotranspiration (ET_a) in three treatments of a summer maize–winter wheat rotation system over five years. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. Different lowercase letters in the three treatments in the same crop growing season indicate significant differences at the $p < 0.05$ level.

3.3. Soil Aggregates

On the whole, there were fewer WSAs > 0.25 mm than <0.25 mm in 2013 and vice-versa in 2016 (Table 4). Water-stable aggregates < 0.25 mm were the dominant size class in all treatments in 2013. Compared to CK, WSAs > 0.25 mm increased significantly in LSM and ALSP, by 9.29% and 35.76% in 2013 and 8.70% and 17.34% in 2016, respectively, with significant differences between LSM and ALSP. Furthermore, LSM and ALSP increased MWD values by 18.37% and 83.67% in 2013 and 10.67% and 29.33% in 2016, respectively.

Table 4. Water-stable aggregates and aggregate stability of the 0–20 cm soil under different treatments.

Year	Treatments	Aggregate Sizes (mm)						MWD (mm)
		>5	>2~5	>1~2	>0.5~1	>0.25~0.5	≤0.25	
2013	CK	2.61 c	3.93 b	4.91 b	9.39 b	11.62 a	67.55 a	0.49 c
	LSM	3.56 b	4.01 b	5.65 ab	10.29 ab	11.97 a	64.53 a	0.58 b
	ALSP	7.21 a	5.81 a	6.20 a	11.88 a	12.97 a	55.94 b	0.90 a
2016	CK	16.74 c	3.86 b	5.20 b	17.13 a	18.23 c	38.86 a	1.50 c
	LSM	18.42 b	5.06 a	5.58 b	17.73 a	19.70 b	33.54 b	1.66 b
	ALSP	22.39 a	4.88 a	7.48 a	15.56 b	21.44 a	28.26 c	1.94 a

Note: Different lowercase letters within a column in the same year indicate significant differences between different treatments at $p < 0.05$. MWD is the mean weight diameter.

3.4. Soil Organic Carbon and Total Nitrogen

The straw returning treatments significantly increased SOC over time (Figure 5). Compared to CK, LSM and ALSP increased SOC in the 0–10 cm soil layer by 13.21% and 15.36%, respectively. Similarly, LSM and ALSP increased SOC in the 10–20 cm soil layer by 4.52–11.95% and 6.63–13.25%, respectively. Compared to 2011, the CK, LSM, and ALSP treatments in 2016 had increased SOC in the 0–10 cm soil layer by 12.14%, 22.03%, and 25.03%, respectively, and the 10–20 cm soil layer by 18.22%, 27.19%, and 32.35%, respectively, with a significant difference between ALSP and LSM in the 10–20 cm soil layer.

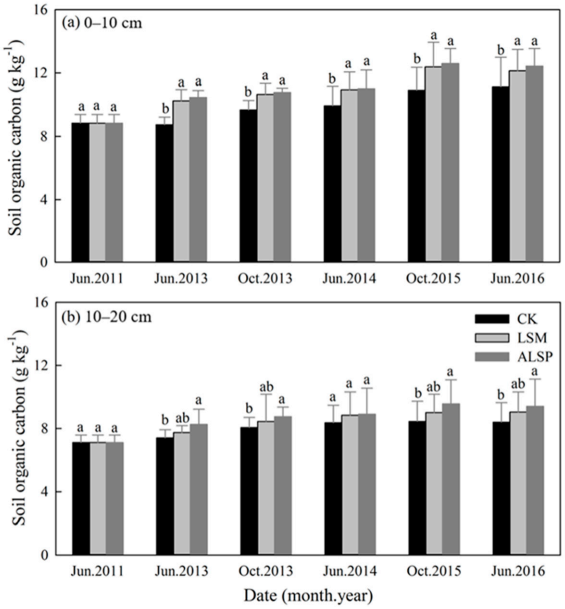


Figure 5. Soil organic carbon properties in the 0–10 cm and 10–20 cm soil layers at the start (2011), middle (2013, 2014, and 2015), and end (2016) of the experimental treatments. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. Different lowercase letters in the three treatments in the same date indicate significant differences at the $p < 0.05$ level.

Straw incorporation increased the soil TN content. After five years of straw returning treatments, LSM and ALSP had 8.1% and 11.8% more TN at the 0–10 cm soil depth than CK, respectively, while at the 10–20 cm soil depth, ALSP had more TN than CK, but LSM did not differ from CK (Figure 6b). From 2011 to 2016, TN increased in the 0–10 cm soil layer by 21.3% in CK, 34.7% in LSM, and 36.2% in ALSP (Figure 6a), and by 15.0% in CK, 16.0% in LSM, and 23.9% in ALSP in the 10–20 cm soil layer (Figure 6b). Soil TN increased more in ALSP than LSM in the 0–20 cm soil layer.

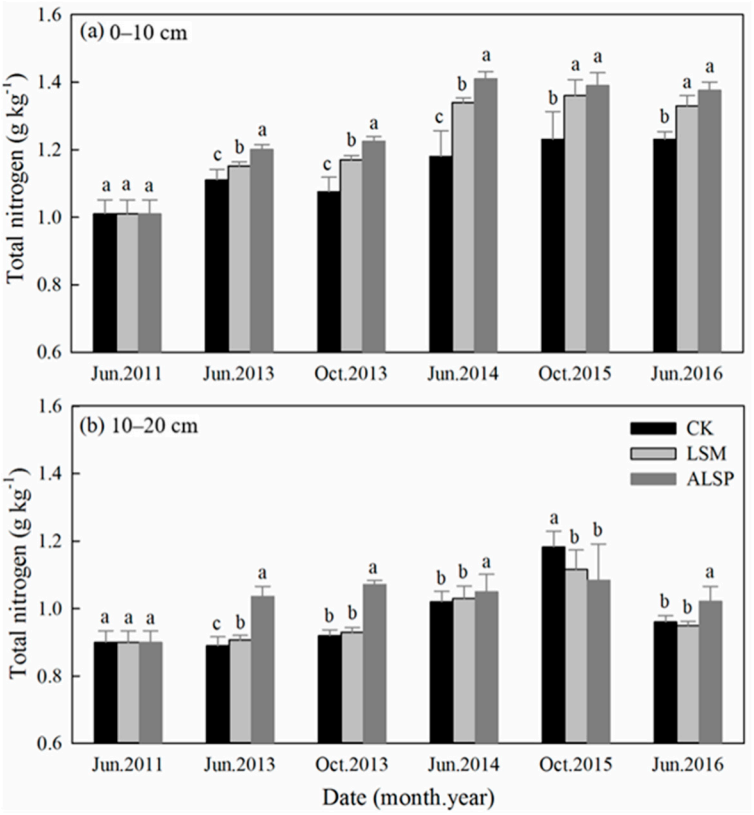


Figure 6. Soil nitrogen properties in the 0–10 cm and 10–20 cm soil layers at the start (2011), middle (2013, 2014, and 2015), and end (2016) of the experimental treatments. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. Different lowercase letters in the three treatments in the same date indicate significant differences at the $p < 0.05$ level.

3.5. Grain Yield and Related Harvest Factors

The five-year mean wheat yields in LSM and ALSP significantly increased by 8.0% and 16.5%, respectively, relative to CK (Table 5), with a significant difference between LSM and ALSP (see Table A1 in Appendix A). The highest mean wheat yield (9464 kg ha^{-1}) occurred in 2011–2012, with 192.3 mm rainfall plus 180 mm irrigation. The lowest mean wheat yield (5173 kg ha^{-1}) occurred in 2015–2016, with 203.3 mm rainfall plus irrigation (Tables 3 and A1).

The five-year mean maize yields in LSM and ALSP increased by 9.7% and 14.3%, respectively, relative to CK (Table 5), and the difference was not significant between LSM and ALSP (Table A1). ALSP had the highest mean annual EWY (14,371 kg ha^{-1}), followed by LSM (13,520 kg ha^{-1}), which increased the mean equivalent annual yield by 15.6% and 8.7%, respectively, relative to CK (12,434 kg ha^{-1}) (Table 5). The highest mean maize yield (9934 kg ha^{-1}) occurred in 2013–2014, with 224.1 mm rainfall and 80 mm irrigation. The lowest mean maize yield (5817 kg ha^{-1}) occurred in 2014–2015, with 379.6 mm rainfall (Tables 3 and A1).

Table 5. Mean grain yields in three treatments of a summer maize–winter wheat rotation system in 2011–2016.

Treatment	Wheat (*Triticum aestivum* L.)		Maize (*Zea mays* L.)		Annual of Equivalent Wheat	
	Yield (kg ha^{-1})	Increasing Rate (%)	Yield (kg ha^{-1})	Increasing Rate (%)	Yield (kg ha^{-1})	Increasing Rate (%)
CK	7194 c	–	7570 b	–	12,434 c	–
LSM	7769 b	8.0	8307 a	9.7	13,520 b	8.7
ALSP	8382 a	16.5	8650 a	14.3	14,371 a	15.6

Note: Different lowercase letters within the same column indicate significant differences at the $p < 0.05$ level. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. Annual of equivalent wheat yield is calculated using the equation: [(maize yield × minimum support price of maize fixed by the Government)/minimum support price of wheat fixed by the Government + winter wheat yield]. Increasing rate is calculated using the equation: [(grain yield in LSM or ALSP − grain yield in CK)/grain yield in CK × 100%].

Mean aboveground biomass increased in LSM and ALSP by 8.8% and 10.2%, respectively, in summer maize, and 4.0% and 13.8%, respectively, in winter wheat (Table A1). The hundred-grain weight of summer maize was higher in ALSP than LSM and CK, while the thousand-grain weight of winter wheat was lower in ALSP than LSM and CK. The mean maize kernels per spike in LSM and ALSP increased by 6.8% and 6.5%, respectively, relative to CK. The mean wheat kernels per spike were also higher in LSM and ALSP than CK each year.

3.6. Water Use Efficiency

The WUE represents the relationship between water consumption and grain yield (Table 6 and Figure 7). The five-year mean WUE of summer maize increased by 11.3% and 16.3% in LSM and ALSP, respectively, relative to CK (Table 6), with a significant difference between LSM and ALSP (Figure 7). The highest mean WUE of summer maize occurred in 2015, with a maize yield of 8346 kg ha^{-1} and ET_a of only 248.2 mm, followed by 2013, 2012, and 2011 (Figure 7). The lowest mean WUE of summer maize occurred in 2014, with a maize yield of only 5817 kg ha^{-1} and ET_a of 307.9 mm (Table A1, Figure 4).

Table 6. Mean WUE in three treatments of a summer maize–winter wheat rotation system in 2011–2016.

Treatment	Wheat (*Triticum aestivum* L.)		Maize (*Zea mays* L.)		Annual of Equivalent Wheat	
	WUE (kg ha^{-1} mm^{-1})	Increasing Rate (%)	WUE (kg ha^{-1} mm^{-1})	Increasing Rate (%)	WUE (kg ha^{-1} mm^{-1})	Increasing Rate (%)
CK	20.4 c	–	22.9 c	–	18.2 c	–
LSM	22.5 b	10.4	25.5 b	11.3	20.1 b	10.5
ALSP	24.3 a	18.9	26.7 a	16.3	21.3 a	17.5

Note: Different lowercase letters within the same column indicate significant differences at the $p < 0.05$ level. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. WUE indicates water use efficiency. Annual of equivalent wheat WUE is calculated using the equation: annual of actual evapotranspiration/[(maize yield × minimum support price of maize fixed by the Government)/minimum support price of wheat fixed by the Government + winter wheat yield]. Increasing rate is calculated using the equation: [(crop WUE in LSM or ALSP − crop WUE in CK)/crop WUE in CK × 100%].

The five-year mean WUE of winter wheat increased by 10.4% and 18.9% in LSM and ALSP, respectively, relative to CK (Table 6), with a significant difference between LSM and ALSP (Figure 7). The mean annual equivalent WUE in ALSP and LSM increased by 17.5% and 10.5%, respectively, relative to CK (Table 6). The highest mean WUE occurred in 2012–2013, with a wheat yield of 8308 kg ha^{-1} and ET_a of 342.1 mm (Figure 7). The lowest mean WUE of winter wheat occurred in 2014–2015, with a wheat yield of 7702 kg ha^{-1} and ET_a of 370.3 mm (Table A1, Figure 4).

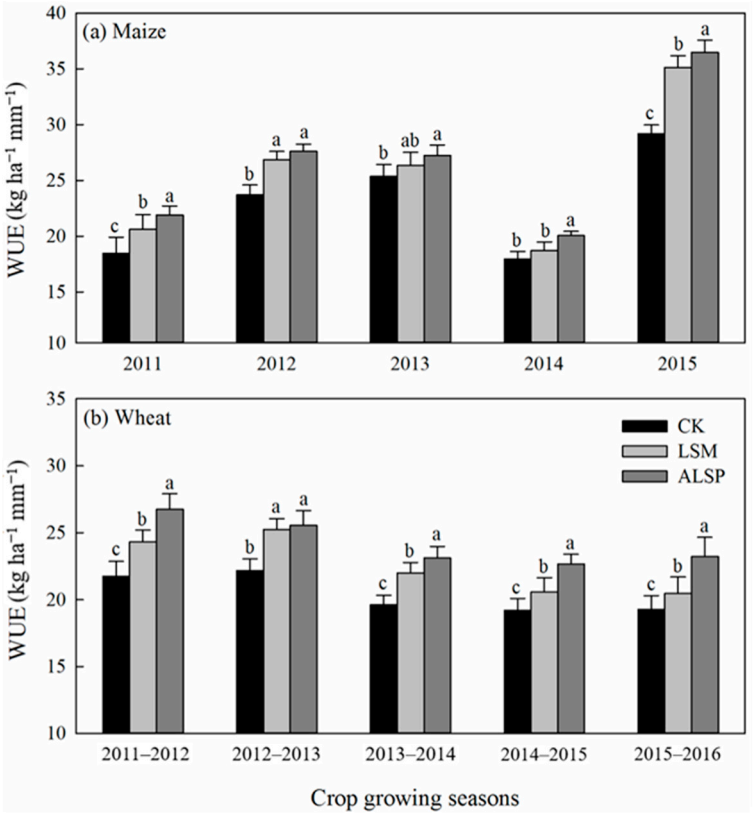


Figure 7. Water use efficiency (WUE) in three treatments of a winter wheat–summer maize rotation system over five years. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil. Different lowercase letters in the three treatments in the same crop growing season indicate significant differences at the $p < 0.05$ level.

3.7. Relationships between Rainfall Plus Irrigation (RI), ET_a, Crop Yield, and WUE

The correlation analysis between RI, ET_a, crop yield, and WUE is in Table 7. RI was significantly correlated with ET_a, crop yield, and WUE in the winter wheat seasons ($r = 0.912$ **, $r = 0.940$ **, and $r = 0.504$ **, respectively). RI was constant and adequate at the critical growth stages in the winter wheat seasons, which increased the crop yield and WUE. However, RI was negatively correlated with the summer maize yield ($r = -0.344$), especially WUE ($r = -0.580$ **).

Table 7. Pearson's correlation of rainfall plus irrigation (RI), ET_a, crop yields, and WUE in three treatments of summer maize and winter wheat in 2011–2016.

Item	Wheat (*Triticum aestivum* L.)				Maize (*Zea mays* L.)			
	RI	ET_a	Yield	WUE	RI	ET_a	Yield	WUE
RI	1				1			
ET_a	0.912 **	1			0.288	1		
Yield	0.940 **	0.876 *	1		−0.344	0.476 *	1	
WUE	0.504 **	0.237	0.674 **	1	−0.580 **	−0.365	0.638 **	1

Note: ET_a indicates the actual evapotranspiration. WUE indicates the water use efficiency. * Correlation is significant at $p < 0.05$ (2-tailed). ** Correlation is significant at $p < 0.01$ (2-tailed).

4. Discussion

4.1. Soil Water

After returning straw to the field, microorganisms in the soil decompose straw into simple compounds through mineralization, while releasing essential nutrients such as N, P, and K for plants [21], which can also enhance the soil water-holding capacity and water availability, thereby promoting crop growth under arid conditions [25]. Song et al. found that combining straw and chemical fertilizer improved the soil moisture conditions to increase maize yields in drought years [26]. In the Hexi Corridor of China, Hu et al. found that crop straw returning successfully increased the pre-sowing soil moisture by 7–10% in a maize–wheat rotation system [27]. In the Loess Plateau of northwestern China, our study revealed that straw returning conserved rainwater and irrigation water in the soil, increasing the soil water in the 0–100 cm soil layer during most of the crop growing seasons, especially in the ALSP treatment (Figure 3a). This was mainly because the incorporation of ammoniated straw combined with N fertilizer significantly improved the physicochemical and biological properties, enhancing rainwater and irrigation water infiltration into the root zone (Figure 3). Other studies have reported that the incorporation of crop straw into the soil improved the soil bulk density, total porosity, and water-holding capacity. In contrast, the CK treatment degraded the soil hydrological properties (Figure 3). Similarly, Pinheiro et al. reported that soil exposure with tillage and a lack of residue inputs promoted low soil water storage and increased susceptibility to erosion [28].

The LSM treatment had lower soil water contents in the 2014–2015 and 2015–2016 crop growing seasons compared to CK (Figure 3a), as the straw mulch promoted maize and wheat growth, thereby using more soil water. Meanwhile, the low rainfall and increased plant growth led to higher transpiration rates, explaining the lower soil water contents in the 2014–2015 and 2015–2016 growing seasons when rainfall and irrigation were not sufficient. Indeed, the effectiveness of straw mulch in conserving soil water might have deteriorated during the dry years (2014–2016) as the straw mulch intercepted small rainfall amounts, preventing it from penetrating the soil. However, when rainfall and irrigation were sufficient in the normal years (2012–2013 and 2013–2014), straw mulch increased soil water storage by reducing the evaporation rate of surface water and enhancing rainwater and irrigation water infiltration into the root zone. The measured ET_a decreased by about 10 mm. Returning straw to the field increased soil organic matter, improved soil permeability, interacted with minerals and microorganisms in the soil to form aggregates, and prevented water and nutrient loss. This aligns with the findings of Akhtar et al. [3], who reported that integrated wheat straw mulch and N fertilizer conserved more rainwater and provided favorable conditions for soil microbes to decompose soil organic matter and release soil nutrients.

In the present study, significant differences in soil water between LSM and ALSP occurred in the 0–20 cm soil layer in the wet year of 2011–2012 (ALSP > LSM) and normal years in 2012–2014 (ALSP < LSM), and in the 20–60 cm soil layer in the dry years in 2014–2016 (ALSP > LSM) (Figure 3). In 2012–2014, LSM reduced soil evaporation and conserved more rainwater than ALSP to alleviate insufficient soil water in the normal years. However, in 2011–2012 and 2014–2016, the increase in soil water storage in ALSP could be attributed to better soil water-holding capacity as ammoniated straw incorporation combined with N fertilizer improved soil aggregation, increased soil aggregate stability, and enhanced soil water retention in the root zone [29], indicating that ALSP could alleviate soil drought and excessive humidity better than LSM, and was essentially a buffer for wet and dry years. These data also indicate that the moisture conserving effect of straw mulch and ammoniated straw incorporation is affected by weather conditions.

4.2. Soil Aggregates

Soil aggregates are the basic units of soil structure, which are affected by soil fauna, microorganisms, roots, organic and inorganic binding agents, and organic materials [30]. The continuous input of either straw mulch or incorporation positively affects soil biological ac-

tivity, and the bio-products released through straw decomposition enhance the aggregation of clay and silt particles, thus increasing soil macroaggregation [31]. Consequently, straw returning significantly increased the soil macroaggregate mass proportion in the 0–20 cm soil layer, relative to CK (Table 4). Halder et al. reported that straw incorporation increased soil aggregation or SOC [32,33]. Our study showed that ALSP significantly increased WSAs > 0.25 mm in the upper soil, relative to LSM, because the straw incorporation increased the contact area between the straw and soil, stimulated the oxidation of SOC, and caused the loessal soil particles to form aggregates [34]. Generally, the lack of soil exposure to crop residue inputs reduces soil aggregation and organic C [28]. In contrast, our study showed that CK increased the mass proportion of macroaggregates from 2013 to 2016 (Table 4), possibly due to residual belowground roots, weeds, undecomposed plants, and nutrients not absorbed by crops after the harvest of the last growing season [35]. The contribution of belowground roots and weed residue to soil aggregates and SOC, relative to crop straw, under varied soil types and climate conditions needs further investigation.

4.3. Soil Organic Carbon and Total Nitrogen

Research has shown that, in regions such as northwest and northeast China [36], as well as the Loess Plateau [37], soil fertility is extensively evaluated using SOC because of its capacity to increase soil aggregate stability, enhance water-holding capacity, and increase crop productivity [20,38]. Straw returning can increase soil organic matter and other soil nutrients to improve crop yields [39]. Our study showed that ALSP and LSM significantly increased SOC in the 0–10 cm soil layer, relative to CK, likely due to the amount of crop straw incorporated into the soil. This agrees with the findings of Yang et al. [12], who reported that straw returning positively affected SOC build-up and soil fertility. This is probably due to crop straw promoting microbial biomass by serving as a substrate for microbial activities and microbes promoting crop growth by transforming organic matter in the soil into available crop nutrients, thereby increasing biomass production and forming a cycle of positive feedback [40].

The application of straw mulch and chemical fertilizers increased SOC and improved soil structure [41]. In the present study, straw mulching enhanced the decomposition of soil organic matter in the upper soil layer (Figure 4). However, compared to the topsoil layer, straw mulching applied on the surface had less influence on the soil properties in the subsoil layer (below 10 cm depth) (Figure 4), which agrees with the findings of Yadav et al. [38]. This may be due to the limited release of C through decomposition and mineralization, which mostly affects to the surface layer [34]. Additionally, ALSP had a higher SOC in the 10–20 cm soil layer than LSM, likely because the low C/N ratio of the incorporated ammoniated straw significantly increased its decomposition and release of nutrients, improved soil aggregate structure, and promoted SOC accumulation in the plow layer.

Total nitrogen is an important parameter for assessing soil quality [42]. Soil runs short of nitrogen when TN is <2 g kg^{-1} [43]. The initial TN in our study was ~1.01 g kg^{-1} in the 0–10 cm soil layer and ~0.82 g kg^{-1} in the 10–20 cm soil layer (Figure 6). Fertilizer management and straw returning are beneficial for accumulating TN and improving TN stocks. After five years of winter wheat–summer maize rotations, LSM and ALSP increased TN concentrations in the 0–20 cm soil layer, relative to CK (Figure 6), which agrees with the findings of Zhang et al. [16]. Straw returning can improve the soil physicochemical conditions (soil aggregation, soil water retention, etc.) in the upper soil, promoting crop growth and returning more root residues to the soil [44]. Topsoil TN increased by 11% in LSM and 12.3% in ALSP after five years of straw incorporation (Figure 6), likely due to an increase in microbial activity and population size along with a significant increase in the amount of mineralized N [45]. Subsequently, these microbial constituents were mineralized for plant uptake or redistributed among more complex and less labile soil organic matter [45]. Compared to TN in 2011, ALSP showed a greater increase in the TN concentration at 10–20 cm soil depth in 2016 because the ammoniated straw with a

low C/N ratio facilitated the N release from crop straw and temporarily immobilized soil mineral N.

Nitrogen is a major yield-limiting factor and is difficult to manage in crop systems, with N dynamics becoming more complex in the presence of different straw returning practices [46]. Our study showed that the TN concentration increased more in ALSP than LSM (Figure 6), mainly because the incorporated ammoniated straw significantly improved the soil physicochemical properties and promoted the accumulation of soil nutrients. The TN concentrations decreased with the soil depth in all treatments, agreeing with the findings of Mi et al. [47], and less so in ALSP and LSM than CK, which agrees with the findings of Hao et al. [48]. The incorporation of ammoniated crop straw is beneficial for the accumulation of TN, thus decreasing soil N losses in the plow layer, improving soil aggregation and soil water retention, and reducing soil bulk density [44].

4.4. Crop Yield and WUE

Crop productivity is significantly influenced by soil water availability and soil fertility. Combining appropriate chemical fertilizers with straw returning or manure amendments helps to stabilize soil structure and improve soil fertility, resulting in higher and more stable yields [39]. For example, straw mulching combined with chemical fertilizer significantly increased wheat yield by 10.9% and maize yield by 13.4% in rainfed dryland regions of China [42]. Straw incorporation combined with N fertilizer increased the yields of winter wheat and summer maize by 16.5% and 13.2%, respectively, in the North China Plain [49]. However, Singh et al. reported that rice yields did not significantly differ between urea and wheat straw applied alone or in combination [50]. Gao et al. reported grain yield reductions in maize and wheat under straw mulch without irrigation [15]. Our study showed that ALSP and LSM significantly increased the mean wheat yield and annual EWY relative to CK (Table 5), which agrees with the findings of Wang et al. [9], who reported that straw incorporation with chemical fertilizers increased crop yields. This suggests that straw returning combined with chemical fertilizer is more efficient than fertilizer alone in alleviating soil water and soil nitrogen limitations to annual wheat and maize growth. Moreover, Yu et al. found that the mixed application of crushed and ammoniated straw and inorganic soil amendment (calcium sulfate) had a more significant effect on increasing winter wheat yield. This strategy increased the yield by 11.12% and 17.85%, respectively, compared to the long straw mulching strategy and by 7.39% and 16.59%, respectively, compared to the long straw plowing strategy in the two growing seasons of winter wheat [13]. The observed disparity may be due to differences in soil type, straw type, fertilizer dosage, or weather conditions.

Generally, the differences in grain yield between LSM and ALSP were significant throughout the experiment. This was mainly attributed to significant improvements in soil nutrient levels and increased soil enzyme activities in the plow layer of ALSP; the continuous application of ammoniated straw and N fertilizer significantly enhanced soil macroaggregate content, improved soil nutrients, and increased the water-holding capacity. Our study also found that ALSP produced higher maize yields in the year with lower rainfall compared to the year with higher rainfall. This is because the ammoniated straw incorporation combined with N fertilizer gathered water and fertilizer in the dry year to alleviate soil water stress [9]. By contrast, excessive rainwater in the wet year increased the soil water content, negatively affecting soil respiration, root development, and crop growth.

Straw incorporation increased soil water content and improved WUE by 17.2–17.5% in the winter wheat season in arid northwest China [51]. The combined use of chemical fertilizers and crop straw increased WUE in the spring maize season [9]. Our study showed that ALSP produced significantly a higher WUE than LSM, suggesting that ammoniated straw incorporation could reduce soil water loss better than straw mulch, ensuring the efficient uptake and utilization of soil water at different crop growth stages. Additionally, the greater increase in the WUE in the winter wheat season compared to the summer maize season may be due to the uneven rainfall distribution and supplemental irrigation in the winter wheat season

(Tables 3 and 4), which affected water use and crop yield. ALSP recorded the highest mean annual WUE of equivalent wheat, indicating that ammoniated straw incorporation combined with N fertilizer promoted a better use of rainwater, irrigation water, and soil nutrients by improving the soil water-holding capacity and soil quality. Overall, the incorporation of ammoniated straw combined with N fertilizer appears to be particularly well-suited to improving soil fertility and increasing the yield and WUE of winter wheat and summer maize in the sub-humid, drought-prone areas of northwestern China.

In the present study, winter wheat yield and its WUE showed a significant positive correlation with rainfall plus irrigation. Similarly, Shao et al. reported a significant positive correlation between rainfall and wheat yield, but no such relationship was evident with maize yield in the semi-arid areas of China [42]. We also found a negative relationship between summer maize yield and rainfall plus irrigation (Table 7), likely due to the extremely uneven and heavy rainfall distribution causing a greater deep water percolation and affecting soil respiration and plant photosynthesis, thereby reducing summer maize yield and WUE. This result also indicates that rainfall plus irrigation is an crucial factor affecting wheat yield in semi-humid, drought-prone areas, whereas summer maize was less efficient at using water than wheat when sufficient rainfall was received during the maize season [42].

5. Conclusions

The combination of straw returning and chemical fertilizer application significantly increased soil macroaggregates, improved SOC and TN levels, and enhanced yields and WUE of summer maize and winter wheat under conditions of uneven rainfall distribution and irrigation. The incorporation of ammoniated straw with a low C/N ratio (25:1) combined with chemical N fertilizer (ALSP) significantly increased the soil water content by 16.24% in the 0–20 cm soil layer and enhanced SOC by 11.29% and TN by 41.68% in the upper soil, relative to the increment in LSM. ALSP alleviated soil drought and humidity caused by uneven rainfall distribution more effectively than LSM, essentially acting as a buffer for extremely wet and dry years. In this study, ALSP significantly increased EWY and WUE by 15.6% and 17.5%, respectively, compared to CK, and by 6.79% and 5.97%, respectively, compared to LSM. Rainfall combined with irrigation significantly affected the actual evapotranspiration, grain yield of winter wheat, and WUE of winter wheat and summer maize in sub-humid, drought-prone areas with uneven rainfall distribution and irrigation. Thus, the incorporation of ammoniated straw combined with N fertilizer is an effective practice for enhancing soil fertility, improving soil water-holding capacity, increasing wheat and maize yields, and improving their WUE in the sub-humid, drought-prone areas of northwestern China and other similar regions in the world. But the research on returning farmland patterns and effects under different soil types or climatic conditions is still insufficient, and long-term experimental tracking studies are needed to accumulate data to determine their positive and negative effects and their regulatory mechanisms on soil.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Aboveground biomass, grain yield, and its components in the three treatments of summer maize and winter wheat in 2011–2016.

Year	Treatment	Maize (*Zea mays* L.)				Wheat (*Triticum aestivum* L.)			
		Kernels (Per Spike)	Mean Weight (g/100 Kernels)	Yield (kg ha^{-1})	Biomass (kg ha^{-1})	Kernels (Per Spike)	Mean Weight (g/1000 Kernels)	Yield (kg ha^{-1})	Biomass (kg ha^{-1})
2011–2012	CK	479.5 b	31.8 b	6432 c	11,886 b	37.3 b	54.6 a	8683 c	18,052 b
	LSM	497.7 a	34.4 a	7045 b	12,988 a	37.9 b	54.3 a	9404 b	18,855 b
	ALSP	498.3 a	34.1 a	7460 a	13,121 a	40.3 a	51.8 b	10,305 a	21,843 a
2012–2013	CK	554.8 b	33.2 b	9113 c	14,996 b	37.2 b	55.3 a	7790 b	15,928 b
	LSM	599.7 a	36.4 a	9981 b	16,084 a	37.7 b	55 a	8438 a	16,638 b
	ALSP	594.3 a	35.1 a	10,316 a	16,231 a	40.1 a	53.8 a	8695 a	17,731 a
2013–2014	CK	535.8 b	30.4 c	9565 c	15,712 b	36.9 b	55.1 a	7545 c	16,767 b
	LSM	588.2 a	33.8 b	9905 b	16,988 ab	37.6 ab	54.8 a	8393 b	17,034 ab
	ALSP	592.9 a	37.6 a	10,331 a	17,487 a	38.6 a	52.6 b	8844 a	17,858 a
2014–2015	CK	457.4 b	21.4 a	5579 b	13,662a	36.8 b	52.8 a	7149 b	14,602 b
	LSM	461.6 b	21.2 a	5822 ab	14,206 a	36.9 b	52.4 a	7580 b	15,517 b
	ALSP	482.7 a	20.4 a	6049 a	14,288 a	38.9 a	50.6 a	8376 a	17,540 a
2015–2016	CK	545.9 b	25.6 a	7160 b	9824 b	38.6 a	50.4 a	4801 b	11,951 b
	LSM	601.7 a	27.8 a	8783 a	11,885 a	38.1 a	49.5 a	5028 b	12,377 ab
	ALSP	618.1 a	27.6 a	9094 a	12,412 a	39.9 a	47.5 b	5691 a	13,005 a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates conventional tillage, nitrogen fertilizer plowed into the soil, and no straw mulching. LSM indicates conventional tillage, nitrogen fertilizer plowed into the soil, and straw mulching. ALSP indicates conventional tillage and ammoniated straw with nitrogen fertilizer plowed into the soil.

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