Article

An Ammoniated Straw Incorporation Increased Biomass Production and Water Use Efficiency in an Annual Wheat-Maize Rotation System in Semi-Arid China

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Abstract: Water shortage and excessive chemical fertilizers application result in low soil water and nutrient availability and limit crop production in the Loess Plateau of Northwest China. Ammoniated straw incorporation with N fertilization may be an efficient strategy to maintain agricultural sustainability. However, the interactive effects of straw incorporation and N fertilizer on the biomass water use efficiency (WUE) in the winter wheat–summer maize rotation system remain unclear. A 3-year field experiment was conducted to evaluate the effects of combining ammoniated straw incorporation and N fertilizer on soil water, biomass yield and biomass water use efficiency (WUE) in an annual summer maize (*Zea mays* L.)—Winter wheat (*Triticum aestivum* L.) rotation system. There were three treatments: (i) long straw (5 cm) mulching with N fertilizer (CK), (ii) long straw with N fertilizer plowed into the soil (LP), and (iii) ammoniated long straw with N fertilizer plowed into the soil (ALP). Compared with the CK treatment, LP and ALP led to a similar soil water storage capacity. ALP improved summer maize biomass yield and winter wheat biomass yield at the jointing-maturity stage. ALP improved summer maize WUE at the ten-leaf collar-tasseling stage and winter wheat WUE from the tillering stage to the maturity stage. Also, the ALP treatment increased the total water use efficiency (TWUE) of winter wheat by 4.1–22.0%. Overall, ammoniated straw incorporation produced the most favorable biomass yield and WUE in the summer maize—Winter wheat rotation system in the Loess Plateau of China.

Keywords: soil water; biomass yield; biomass water use efficiency; ammoniated straw incorporation

1. Introduction

Water shortage is one of the urgent global problems that threaten the development of sustainable agriculture and long-term food security [1]. The Loess Plateau is one of the major grain-producing areas in the northwest of China. However, water shortage and excessive chemical fertilizers application have caused soil degradation, resulting in low soil water and nutrient availability and limiting the agricultural production in this region [2,3]. Straw incorporation is generally considered to be beneficial

for long-term soil quality and soil water availability [4]. In order to improve soil water and fertilizer availability and meet the increasing food demand, the practices of straw incorporation, including straw mulching, straw plowed into the soil and ammoniated straw plowed into the soil, have become widely used techniques for improving soil water and nutrient availability and increasing crop yields [5–8].

Straw incorporation can reduce the application of mineral fertilizers [9], improve soil biophysical properties [10] and soil water [11], reduce nutrient losses from run-off and leaching [12–14], and support sustainable crop production in cropping systems [15]. In recent years, straw incorporation has been widespread in the winter wheat–summer maize double-cropping system in northwest China. This is mainly due to the increased use of machinery that leaves the straw on the land in response to a ban by the Chinese government on straw burning. On the other hand, the return of both maize and wheat straw may be the best strategy for improving soil structure, soil organic carbon, and crop yield [16]. Specifically, straw mulching can reduce evaporation loss from the soil surface, enhance soil aggregation, and promote biological activity [17–20]. However, some research presented that low soil temperature caused by straw mulching froze wheat seedlings and roots during the winter, thereby negatively influencing germination and tillering [21]. In addition, the incorporation of crop straw with high lignin and cellulose contents, such as maize and wheat straw, is not conducive to crop growth due to the slow decomposition rate of crop straw [4]. Therefore, straw mulching has not always been shown to increase, but also to decrease yields [22–24]. Compared with straw mulching, straw decomposition is faster when straw is incorporated into the soil, which improves soil aggregate stability and increases crop yields [8,25]. However, returning straw to the soil may have a negative effect on crop growth because of N immobilization [26]. During straw decomposition, soil microorganisms and decomposed crop straw are competing for the same N source, resulting in nitrogen starvation for field crops [27]. A lower C/N ratio can decrease the negative effect of straw incorporation on crop growth [8,28]. Some studies found that straw ammoniated with urea could result in a low C/N ratio of crop straw with lignin and cellulose contents [29,30]. Our team previously reported that ammoniated crop straw plowed into the soil was an effective method for improving soil aggregate stability and soil water retention, decreasing the C/N ratio of crop straw and increasing crop yields in the Loess Plateau of Northwest China [8].

To date, most studies have focused on the effects of straw incorporation with N fertilization practices on soil properties and crop yields [7,21]. However, the interactive effects of different straw incorporation and N fertilization practices on the crop growth and biomass water use efficiency in the winter wheat–summer maize rotation system remain unclear. Hence, the objective of this study is to investigate the effect of ammoniated crop straw incorporation on soil water characteristics, biomass yield and WUE of summer maize and winter wheat at different growth stages in the southern region of Loess Plateau, China.

2. Materials and Methods

2.1. Experimental Site

Field experiments with summer maize and winter wheat were conducted from June 2011 to June 2014 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. The experimental site is characterized by low and erratic rainfall with drought occurring at different growth stages of winter wheat and summer maize. The mean annual air temperature is about 13 °C. The mean annual rainfall is about 600 mm, with 60% falling between July and September. The rainfall distribution and air temperature were recorded over the whole period of the experiment. From 2011 to 2014, the rainfall during the summer maize growth season was 616.5, 432.5 and 224.1 mm, respectively (Figure 1a), and the rainfall during the winter wheat growth season was 192.3, 223.7 and 298.2 mm, respectively (Figure 1b). The groundwater level was approximately

50 m. The experimental soil was a silt clay loam with a mean bulk density of 1.45 g cm^{-3} in the 0–100 cm soil layer.

Figure 1. Precipitation distributions at different crop growth stages in 2011–2014 winter wheat-summer maize rotation seasons. SJ indicates sowing-jointing stage; JL indicates jointing-ten leaf collar stage; TT indicates ten leaf collars-tasseling stage; TF indicates tasseling-grain filling stage; FM indicates grainfilling-maturity stage; ST indicates sowing-tillering stage; TJ indicates tillering-jointing stage; JT indicates jointing-tasseling stage.

2.2. Experimental Design

This experiment had three treatments: (i) long straw (5 cm) mulching (cover) with N fertilizer (CK), (ii) long straw with N fertilizer plowed into the soil (LP), and (iii) ammoniated long straw with N fertilizer plowed into the soil (ALP). The three treatments were arranged into a randomized complete block design with three replications. Each plot was 5 m long and 4 m wide.

The chemical fertilizers consisted of 120 kg N ha^{-1} as $\text{CO}(\text{NH}_2)_2$ and 54 kg P ha^{-1} as $\text{Ca}(\text{H}_2\text{PO}_4)_2$ for summer maize and the same dose of fertilizers was applied in winter wheat plot. The fertilizers' application under the ALP treatment comprised two parts: The first part of 68 kg N ha^{-1} and 54 kg P ha^{-1} were evenly broadcast before sowing to summer maize or winter wheat plots, and the remaining 52 kg N ha^{-1} was used to ammoniate 4.0 t air-dried long straw (5 cm), which was also plowed into the soil before sowing. The ammoniated long straw was obtained as follows: (1) 112 kg urea (52 kg N) and 120 kg calcium hydroxide were dissolved in water of 2.0 t; (2) the aqueous solution was evenly

sprayed on 4.0 t air-dried crop straw (5 cm in length) to obtain a straw C/N ratio of approximately 25/1; (3) crop straw was mixed and sealed in airtight plastic bags, which were placed for 5 days at room temperature of 26 °C. To keep the same fertilizer application, a full dose of 120 kg N ha⁻¹ and 54 kg P ha⁻¹ was evenly broadcast before sowing to maize or wheat plots for the CK and LP treatments. Winter wheat straw (5 cm in length) of 4.0 t ha⁻¹ was applied in the summer maize plot and summer maize straw (5 cm in length) of 4.0 t ha⁻¹ was applied in the winter wheat plot before sowing under the LP treatment and after sowing under the CK treatment, respectively. Thus, the fertilizers in the CK treatment and the straw and fertilizers in the LP and ALP treatments were plowed into the upper soil layer (0–20 cm) by rotary tillage before sowing.

Wheat seeds (cv. *Xiaoyan-22*) were sown at a density of 150 kg ha⁻¹ from 16 to 19 October and harvested from 5 to 8 June in each growing season. Winter wheat was planted with 25 cm wide row space. The plots were irrigated with 180 mm water during the 2011–2012, 120 mm water during the 2012–2013, and 60 mm water during the 2013–2014 growing season due to drought stress, respectively. Maize seeds (cv. *Qinlong-11*) were sown at a density of 50,000 plants ha⁻¹ from 9 to 19 June and harvested from 1 to 12 October in each growing season. Three treatments involved alternating wide and narrow row spacing of 60 cm and 30 cm. The plots were irrigated with 80 mm during the 2013 growing season and not irrigated during the other growing seasons.

2.3. Sampling and Analysis Methods

2.3.1. Crop Evapotranspiration

During each summer maize or winter wheat growing season, soil water content was measured gravimetrically at 20 cm intervals within the 0–100 cm profile in each plot at sowing stage, jointing stage, ten leaf collar stage, tasseling stage, filling stage, and maturity stage for summer maize; and at sowing stage, tillering stage, jointing stage, tasseling stage, filling stage, and maturity stage for winter wheat, respectively.

Soil water storage was calculated as follows:

$$SW_i = 20 \times S_{wc} \times h \times d \quad (1)$$

where i = sowing, jointing, ten leaf collars, tasseling, grainfilling, and maturity stages for summer maize; and sowing, tillering, jointing, tasseling, grainfilling, and maturity stages for winter wheat. SW_i is the soil water storage (mm); S_{wc} is the gravitational water content (%); h is the soil depth (cm); and d is the soil bulk density (g cm⁻³). Soil water storage was calculated at the 0–60 cm soil depth, while that for calculating evapotranspiration was at the 0–100 cm soil depth.

Actual evapotranspiration at the j th stage (ET_j) was calculated by using the soil water balance equation:

$$ET_j = P_j + I_j - D_j - R_j - \Delta S_j \quad (2)$$

where j = jointing-sowing, ten leaf collars-jointing, tasseling-ten leaf collars, grainfilling-ten leaf collars, and maturity-ten leaf collar stages for summer maize; and tillering-sowing, jointing-tillering, tasseling-jointing, grainfilling-tasseling, maturity, and grainfilling stages for winter wheat.

P_j is rainfall (mm); I_j is the irrigation depth (mm); R_j is runoff loss from ground surface (mm); D_j is vertical soil water exchange at the depth of 100 cm, positive downward, negative upward (mm); and ΔS_j is the difference in soil water storage in the 100 cm soil layer (mm). In this study, the groundwater table remains at the depth of about 50 m below the surface, and irrigation and rainfall were low, so the upward flow and downward flow into the root were negligible, except for the 2011–2012 summer maize season due to extremely heavy precipitation. In addition, surface runoff is omitted due to the deep groundwater table and the experimental field being relatively flat.

2.3.2. Biomass Yield and Water Use Efficiency

Dry biomass yield was measured at each crop growth stage. All the samples of maize and wheat were first dried in an oven at 105 °C for 1 h and then dried at 75 °C to constant weight. Three maize plants were selected per plot and were used to investigate dry aboveground biomass at each growth stage. Winter wheat biomass was determined in each plot by hand harvesting two rows of wheat (50 cm in length) at each growth stage.

Biomass water use efficiency (WUE) was defined as:

$$WUE_j = \frac{BY_j}{ET_j} \quad (3)$$

where BY_j is the dry biomass yield at the j th stage, kg ha^{-1} ; and ET_j is the j th growth stage evapotranspiration (mm).

Total biomass water uses efficiency (TWUE) was defined as:

$$TWUE = \frac{BY_m}{ET_a} \quad (4)$$

where BY_m is the dry biomass yield at the maturity stage, kg ha^{-1} ; and ET_a is the actual evapotranspiration during the whole crop growth season, which is the evapotranspiration sum of different crop growth stages (mm).

2.3.3. Crop Yield

At maturity, grain yields were determined by hand-harvesting two adjacent center rows (90 cm wide and 500 cm long) for maize and four rows (100 cm wide and 100 cm long) for wheat in each plot. Harvest samples were sun-dried for 6–10 days and weighed after threshing. Grain yields of wheat and maize were calculated when the water content in sun-dried grain was about 13% (measured by oven-drying method).

2.4. Statistical Analysis

The data were analyzed using ANOVA on SPSS Multiple comparisons of mean values, which were performed using Least significant difference method at the level $P\text{-value} \leq 0.05$.

3. Results

3.1. Soil Water Storage at Different Growth Stages

The soil water storage (SWS) among three straw incorporation treatments at different growth stages of summer maize are shown in Table 1. At the jointing stage, SWS with the LP treatment was slightly higher than that with the CK treatment in 2011 and 2013. SWS with the ALP treatment were higher by 4.9% than that with the CK treatment in 2013, although the difference was not significant in 2011 and 2012. At the ten-leaf collar stage, the LP and ALP treatment compared with the CK treatment decreased soil water storage by 7.2% and 5.5% in 2012, respectively. At the tasseling stage, SWS with the LP treatment was lower by 5.9% in 2012 than that with the CK treatment. At the grain filling stage, SWS with the LP and ALP treatments were lower by 5.6% and 9.6% than that with the CK treatment in 2013, respectively. At the maturity stage, SWS with the LP treatment was lower by 4.2% and 4.9% than that with the CK treatment in 2012 and 2013, respectively, whereas the difference of SWS between the ALP and CK treatments was not significant.

The changes of SWS varied among three straw incorporation treatments at different growth stages of winter wheat in 2011–2014 (Table 2). At the tasseling stage, SWS with the LP and ALP treatments were higher by 5.3% and 4.2% in 2011–2012 than that with the CK treatment, respectively. However,

the differences among the LP, ALP and CK treatments were not significant at the other growth stages in three winter wheat seasons.

Table 1. Soil water storage in the 0–60 cm soil layer at various growth stages of summer maize as influenced by different straw incorporation treatments.

Years	Treatments	Soil Water Storage (mm)					
		Sowing Stage	Jointing Stage	Ten Leaf Collar Stage	Tasseling Stage	Filling Stage	Maturity Stage
2011	CK	141.86 a	150.98 a	183.64 a	153.04 a	192.82 a	191.13 a
	LP	141.86 a	152.65 a	184.80 a	157.90 a	194.18 a	194.60 a
	ALP	141.86 a	154.99 a	182.27 a	153.41 a	193.37 a	193.93 a
2012	CK	147.04 b	149.53 a	137.32 a	161.02 a	182.23 ba	176.53 a
	LP	154.75 a	148.15 a	127.50 b	151.45 b	179.35 b	169.06 b
	ALP	150.40 ab	154.78 a	129.81 b	157.30 a	186.54 a	174.96 a
2013	CK	180.55 a	164.77 b	141.97 a	129.06 a	120.13 a	150.84 a
	LP	180.15 a	167.21 ab	142.18 a	129.26 a	113.44 b	143.39 b
	ALP	177.36 a	172.86 a	143.65 a	130.60 a	108.54 b	146.57 ab

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

Table 2. Soil water storage in the 0–60 cm soil layer at various growth stages of winter wheat as influenced by different straw incorporation treatments.

Years	Treatments	Soil Water Storage (mm)					
		Sowing Stage	Tillering Stage	Jointing Stage	Tasseling Stage	Filling Stage	Maturity Stage
2011–2012	CK	188.72 a	175.63 a	135.34 a	115.92 b	168.90 a	149.11 a
	LP	188.80 a	174.22 a	136.16 a	122.01 a	164.90 a	148.48 a
	ALP	187.64 a	170.71 a	133.48 a	120.76 a	170.54 a	152.58 a
2012–2013	CK	172.99 a	165.96 a	192.25 a	129.22 a	116.37 a	178.72 a
	LP	175.15 a	163.32 a	188.13 a	129.18 a	118.91 a	176.73 a
	ALP	175.68 a	158.61 a	191.15 a	124.63 a	115.53 a	178.68 a
2013–2014	CK	151.32 a	155.59 a	150.11 a	188.66 a	154.18 a	123.93 a
	LP	154.80 a	152.10 a	147.54 a	191.64 a	153.03 a	124.54 a
	ALP	153.86 a	150.83 a	146.16 a	187.26 a	155.75 a	127.90 a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

3.2. Biomass Yield

Biomass yield of summer maize was affected by different straw incorporation treatments in 2011–2013 (Table 3). The summer maize biomass yields were similar between CK and LP in 2011 and 2012 except for the ten-leaf collar stage in 2011 and jointing stage in 2012. Compared with CK, LP decreased summer maize biomass yield in 2013 except for the maturity stage (Table 3). The ALP treatment improved biomass yields at the jointing-grain filling stage in 2011 and 2012, respectively, but resulted in lower biomass yield at the jointing stage in 2013. Specifically, biomass yields with the ALP treatment were increased by 5.7–12.8%, 6.9–18.4%, 6.9–14.7%, and 16.8–31.4% at the jointing, ten leaf collars, tasseling and grain filling stages in 2011 and 2012 compared with the CK treatment, respectively. The ALP treatment compared with the LP treatment increased biomass yields at different growth stages. Specifically, the ALP treatment improved biomass yields by 11.8–13.4%, 5.6–28.4% and 10.8–15.5% at the ten-leaf collar, tasseling, and grain filling stages, respectively, except for the ten-leaf collar stage in 2011. In addition, biomass yields with the ALP treatment were higher than that with the LP treatment at the jointing stage in 2011 (6.5%) and at the maturity stage in 2013 (5.6%), respectively.

Table 3. Effects of different straw incorporation treatments on biomass yield at different growth stages of summer maize.

Years	Treatments	Biomass Yield (kg ha ⁻¹)				
		Jointing Stage	Ten Leaf Collar Stage	Tasseling Stage	Grain Filling Stage	Maturity Stage
2011	CK	1194 b	2633 b	5093 b	8280 c	12,988 a
	LP	1265 b	2905 a	5159 b	8729 bc	13,027 a
	ALP	1347 a	2814 a	5449 a	9668 a	13,121 a
2012	CK	1327 b	3915 b	5998 b	12,479 b	16,084 a
	LP	1409 a	4149 b	5736 b	12,412 b	15,630 a
	ALP	1403 a	4637 a	6879 a	14,773 a	16,231 a
2013	CK	2073 a	4747 a	8650 a	15,003 a	16,988 ab
	LP	1890 b	3690 b	6465 b	12,704 b	16,556 b
	ALP	1837 b	4439 a	8301 a	14,677 a	17,487 a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

Biomass yield of winter wheat was also affected by the different straw incorporation treatments over the 3 years (Table 4). Compared with the CK treatment, the LP treatment improved biomass yield at the tillering stage in 2011 and resulted in higher biomass yield at the jointing-maturity stage in 2011–2014, except for the maturity stage in 2013–2014 (Table 4). Specifically, biomass yields with the LP treatment were increased by 11.2–23.6%, 4.5–17.2%, 7.4–12.1%, and 4.6–12.1% at the jointing, tasseling, grain filling, and maturity stages, respectively. The ALP treatment improved biomass yield at the tillering-maturity stage in 2011–2014, except for the tillering stage in 2012–2013. Specifically, biomass yields with the ALP treatment were increased by 13.0–22.8%, 14.7–16.1%, 5.8–18.8%, 9.4–23.9%, and 4.7–17.6%, respectively. The ALP treatment improved biomass yields by 4.9% at the grain filling stage and 4.9% at the maturity stage in 2011–2012, 18.3% at the tillering stage, and 14.4% at the grain filling stage in 2013–2014, respectively. In addition, the ALP treatment decreased biomass yield by 7.2% at the jointing stage in 2012–2013.

Table 4. Effects of different straw incorporation treatments on biomass yield at different growth stages of winter wheat.

Years	Treatments	Biomass Yield (kg ha ⁻¹)				
		Tillering Stage	Jointing Stage	Tasseling Stage	Grain Filling Stage	Maturity Stage
2011–2012	CK	428 c	5173 b	14,112 b	16,594 c	18,857 c
	LP	455 b	6097 a	16,388 a	18,609 b	21,147 b
	ALP	484 a	5999 a	15,801 a	19,516 a	22,177 a
2012–2013	CK	353 a	6397 c	9270 b	15,343 b	16,638 b
	LP	311 b	7906 a	10,310 a	16,480 a	17,408 a
	ALP	309 b	7334 b	9807 a	16,780 a	17,732 a
2013–2014	CK	446 b	4432 b	7859 b	12,008 c	17,368 b
	LP	463 b	4927 a	9213 a	13,006 b	17,754 ab
	ALP	548 a	5145 a	9336 a	14,880 a	18,191 a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

3.3. Biomass Water Use Efficiency (WUE) at Different Growth Stages

The WUE of summer maize was affected by different straw incorporation treatments in 2011–2013 (Table 5). At the sowing-jointing stage, WUEs with the LP and ALP treatments were higher by 7.8%, 23.9% in 2011 and lower by 12.0%, 14.1% in 2013 than the CK treatment, respectively. At the jointing-ten

leaf collar stage, WUEs with the LP and ALP treatments were decreased by 7.2%, 12.4% in 2011 and 31.5%, 31.0% in 2013, respectively, although the difference was not significant in 2012. Compared with the CK treatment, at the ten-leaf collar-tasseling stage, WUE with the LP treatment was decreased by 24.1% in 2013 and WUEs with the ALP treatment were increased by 8.8% in 2011 and 22.4% in 2012, respectively. At the tasseling-grain filling stage, WUEs were increased by 5.7–25.2% with the LP treatment and 10.9–43.5% with the ALP treatment in 3 years, respectively. At the grain filling-maturity stage, WUEs with the LP and ALP treatments were decreased by 11.3% and 11.9% in 2012 but increased by 18.9% and 12.1% in 2013, respectively. Compared with the LP treatment, WUEs with the ALP treatment were increased by 4.9% at the sowing-jointing stage in 2011, 7.2–29.6% at the ten-leaf collar-tasseling stage, and 4.9–15.8% at the tasseling-grain filling stage in 2011–2013, respectively.

Table 5. Effects of different straw incorporation treatments on biomass water use efficiency at different growth stages of summer maize.

Years	Treatments	Biomass Water Use Efficiency (kg ha ⁻¹ mm ⁻¹)				
		Sowing-Jointing Stage	Jointing-Ten Leaf Collar Stage	Ten leaves Collar-Tasseling Stage	Tasseling-Filling Stage	Filling-Maturity Stage
2011	CK	15.2 c	264.3 a	120.3 b	119.9 c	92.0 a
	LP	16.4 b	245.4 b	122.1 b	134.8 b	89.1 a
	ALP	18.9 a	231.6 c	130.9 a	156.1 a	90.2 a
2012	CK	12.0 a	135.4 a	154.5 b	72.3 c	330.7 a
	LP	11.9 a	131.3 a	146.0 b	90.5 b	293.4 b
	ALP	12.3 a	131.9 a	189.1 a	103.7 a	291.4 b
2013	CK	12.3 a	57.8 a	258.0 a	288.9 c	419.9 b
	LP	10.8 b	39.6 b	195.7 b	305.2 b	499.4 a
	ALP	10.5 b	39.9 b	251.1 a	320.3 a	470.9 a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

The WUE of winter wheat was affected by different straw incorporation treatments in 2011–2014 (Table 6). At the sowing-tillering stage, WUEs with the LP and ALP treatments were lower by 25.0% and 33.7% in 2012–2013 and 20.0% and 17.5% in 2013–2014 than that with the CK treatment, respectively. Compared with the CK treatment, WUEs were increased by 15.1–20.4% with the LP treatment and 18.2–23.6% with the ALP treatment at the tillering-jointing stage; 18.2–35.5% with the LP treatment and 16.8–17.4% with the ALP treatment (except for that in 2012–2013) at the jointing-tasseling stage; 6.9–23.9% with the LP treatment (except for that in 2012–2013) and 33.5–37.4% with the ALP treatment at the tasseling-grain filling stage; and 6.6% with the LP treatment (except for that in 2012–2013 and 2013–2014) and 5.7–35.4% with the ALP treatment at the grain filling-maturity stage in 2011–2014, respectively. Compared with the LP treatment, WUEs with the ALP treatment were decreased by 11.6% at the sowing-tillering stage in 2012–2013 and increased by 13.4–21.6% at the jointing-tasseling stage (except for that in 2012–2013), 10.9–39.7% at the tasselin-grain filling stage, and 4.7–27.0% at the grain filling-maturity stage in 2011–2014, respectively.

Different straw incorporation treatments affected TWUE during the three-summer maize-winter wheat rotation seasons (Figure 2). The LP treatment compared with the CK treatment decreased TWUE by 4.9% in 2012 and 5.0% in 2013 summer maize seasons, and increased TWUE by 14.0% in the 2011–2012 winter wheat season, respectively. The ALP treatment increased TWUE of winter wheat by 4.1–22.0% compared with the CK treatment in 2011–2014. Compared with the LP treatment, the ALP treatment increased TWUE of winter wheat by 3.1–7.0% in 2011–2014 and that of summer maize by 6.0% in 2012 and 7.0% in 2013, respectively. In addition, the annual TWUE of maize and wheat with the ALP treatment was higher by 3.1–13.0%, 4.1–5.0% than that with the LP and CK treatments, respectively.

Table 6. Effects of different straw incorporation treatments on biomass water use efficiency at different growth stages of winter wheat.

Years	Treatments	Biomass Water Use Efficiency ($\text{kg ha}^{-1} \text{mm}^{-1}$)				
		Sowing-Tillering Stage	Tillering-Jointing Stage	Jointing-Tasseling Stage	Tasseling-Filling Stage	Filling-Maturity Stage
2011–2012	CK	4.4 a	35.3 b	306.9 c	281.8c	367.8c
	LP	4.5 a	42.5 a	415.9 a	349.1b	391.9b
	ALP	4.4 a	43.6 a	360.3 b	387.2a	497.8a
2012–2013	CK	11.5 a	63.8 b	92.1 b	531.5b	225.2b
	LP	8.6 b	74.7 a	112.6 a	519.5b	223.3b
	ALP	7.6 c	75.4 a	88.3 b	726.0a	260.0a
2013–2014	CK	17.8 a	36.4 b	114.7 b	131.8c	231.1b
	LP	14.2 b	41.9 a	135.5 a	140.9b	233.2b
	ALP	14.7 b	44.1 a	133.9 a	176.0a	244.3a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

Figure 2. Effects of straw incorporation treatments on biomass water use efficiency in winter wheat season, summer maize season and annual maize and wheat season. Bars with the same letter for the same year are not different at $p = 0.05$. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

3.4. Crop Yield

The maize yields of the ALP treatment over 3 years were higher than that of the CK treatment (Table 7). Compared to the CK treatment, the ALP treatment increased the wheat grain yields in 2012 and 2014 (Table 7). There were significant differences in maize yields between the LP and ALP treatments. However, there were no significant differences in wheat yields between the LP and CK treatments.

Table 7. Crop yields at harvest time in 2011–2014 growing seasons [8].

Crop Types	Treatments	Yields (kg ha ⁻¹)			
		2011	2012	2013	2014
Maize	CK	7045 b	9981 b	9905 b	—
	LP	7178 b	9852 b	9695 c	—
	ALP	7460 a	10316 a	10,331 a	—
Wheat	CK	—	9404 b	8438 a	8393 b
	LP	—	9730 b	8528 a	8517 b
	ALP	—	10,305 a	8695 a	8844 a

Note: Different lowercase letters within the same annual column indicate significant differences at the $p < 0.05$ level. CK indicates long straw (5 cm) mulching with N fertilizer. LP indicates long straw with N fertilizer plowed into the soil. ALP indicates ammoniated long straw with N fertilizer plowed into the soil.

3.5. Relationship Among Rainfall Plus Irrigation (RI), ET_a, BY and TWUE

Correlation analysis between RI, ET_a, BY, and TWUE at different growth stages was listed in Table 8. RI was correlated with ET_a and BY in the winter wheat season ($r = 0.919^{**}$ and $r = 0.803^{**}$, respectively), indicating that higher RI increased ET_a and improved winter wheat biomass yield. However, a negative correlation was observed between RI and ET_a, BY, and TWUE in the summer maize season ($r = -0.941^{**}$, $r = -0.974^{**}$, and $r = -0.940^{**}$, respectively). ET_a had a smaller positive correlation with BY ($r = 0.567$) and a smaller negative correlation with WUE in the winter wheat season ($r = -0.130$), indicating that higher ET_a increased BY but decreased WUE of winter wheat. This was because the dry mass of the plant and that of each plant component tended to increase with seasonal ET_a [31]. However, ET_a presented a positive correlation with BY and TWUE in the summer maize season ($r = 0.948^{**}$ and $r = 0.866^{**}$, respectively). Correlation analysis revealed a positive correlation between BY and TWUE in the winter wheat season ($r = 0.742^{*}$) and summer maize season ($r = 0.980^{**}$). This indicated that higher BY resulted in higher TWUE.

Table 8. Pearson correlation of rainfall plus irrigation (RI), ET_a, BY, and TWUE in the three straw incorporation treatments during 2011–2014.

Items	Wheat (<i>Triticum aestivum</i> L.)				Maize (<i>Zea mays</i> L.)			
	RI	ET _a	BY	TWUE	RI	ET _a	BY	TWUE
RI	1				1			
ET _a	0.919 **	1			−0.941 **	1		
BY	0.803 **	0.567	1		−0.974 **	0.948 **	1	
TWUE	0.219	−0.130	0.742 *	1	−0.940 **	0.866 **	0.980 **	1

Note: * Correlation is significant at $p < 0.05$ (2-tailed). ** Correlation is significant at $p < 0.01$ (2-tailed).

4. Discussion

4.1. Effects of Different Straw Incorporation Modes on Soil Water

Long-term addition of crop straw can improve soil water-holding capacity and soil water availability [32]. Soil moisture was not affected by three treatments largely because the differences of the soil water-holding capacity among the three treatments were offset by higher precipitation in

2011 (616.5 mm in 2011, 432.5 mm in 2012 and 224.1 mm in 2013, shown in Figure 1a). Specifically, a significant higher soil water content was observed for the CK treatment compared with the LP treatment at the ten-leaf collar-maturity stage in 2012 (432.5 mm rainfall), indicating that the rate of water vapor flux through mulched straw was generally slow compared with the rate of water loss from a moist soil surface and straw mulching increased water infiltration into soil [33]. However, the ALP treatment compared with the CK treatment led to a significant decrease in soil water storage only at the ten-leaf collar stage in 2012, which indicated that ammoniated straw could rapidly decompose and reduce soil macro-pores induced by crop straw plowed into the soil, resulting in higher soil water-holding capacity. Crops were growing in a water-deficit condition, therefore, utilizing soil moisture in the upper soil profile rapidly. There was no difference among the three treatments at the sowing-tasseling stage in 2013. Additionally, limited precipitation limited infiltration and soil moisture percolation, leading to very little recharge during the experimental period [34].

Some works found that rational coupling of straw incorporation and N fertilizer can reduce the field water consumption at the sowing-jointing stage of wheat [18]. Soil moisture storage in the 0–60 cm soil layer was not affected by three treatments largely because of the low precipitation, which led to soil water being depleted by soil evaporation and plant transpiration and the plots being irrigated with 180 mm in 2011–2012, 120 mm in 2012–2013 and 60 mm in 2013–2014. This resulted in the differences among three straw incorporation treatments being non-significant at the corresponding wheat growth stages. Specifically, the higher soil water content in the 0–60 cm soil layer was observed for the LP and ALP treatments compared with the CK treatment at the tasseling stage. This was mainly because the effectiveness of straw mulching in reducing soil evaporation weakened with natural decomposition [35,36]. On the other hand, the increase in soil water could be attributed to better soil water retention as the crop straw plowed into the soil (LP and ALP) could improve soil physical properties and thus conserve more soil water than the CK treatment did.

It is noted that straw mulching shaded the soil surface, preventing soil water loss by evaporation and thus helping to retain moisture [37]. Hu et al. found that crop residue management practices successfully increased pre-sowing soil moisture by 7–10% in a wheat-maize rotation system in the Hexi Corridor of China [38]. Su et al. observed that straw mulching improved in-season/postseason soil water conservation on the Loess Plateau [39]. Our study showed that ammoniated crop straw presented similar soil water-holding capacity compared with the straw mulching treatment.

4.2. Biomass Yield and Water Use Efficiency

With a lack of timely precipitation under arid or semi-arid conditions, straw incorporation practices can improve soil water status and play an important role in crop growth [36]. However, the anaerobic decomposition of crop straw incorporated to the soil will release some toxic aliphatic aromatic acids and organic acids [40] and restrain crop growth in flooded soil [41]. Our study showed that the ALP treatment compared with the CK treatment improved biomass yields at the jointing-grain filling stage in 2011 and 2012 summer maize seasons. This was mainly because ammoniated straw could enhance soil aggregation, promote biological activity, and improve the soil C/N ratio, resulting in better crop growth environment and higher biomass yield at different crop growth stages. Biomass yield with the LP treatment was decreased by 8.8%–25.3% at the jointing-grain filling stages in 2013 compared with the CK treatment. This was likely due to lower topsoil bulk density and soil macro-pores, which resulted in a lower soil water content and poor crop growth environment when crop straw was plowed into the soil. Our study showed that biomass yield with the ALP treatment was higher by 5.6–28.4% than that with the LP treatment at the ten-leaf collar–Grain filling stage. The probable reason was that soil moisture and fertility with the ALP treatment met the demands of higher biomass yield compared with the LP treatment in 2011–2013. Therefore, in the long term, the rational straw incorporation practice for improving biomass yield of summer maize was the ALP treatment. The LP and ALP treatments compared with the CK treatment basically improved winter wheat biomass yield at the jointing-maturity stage in 2011–2014. This was mainly because straw incorporation with N fertilization

effectively alleviated soil carbon and nitrogen imbalance, improved soil nitrogen concentration, and increased wheat biomass yield [42]. In addition, the ALP treatment compared with the LP treatment improved biomass yield at the maturity stage in 2011–2014, indicating that ammoniated straw could rapidly decompose, increase soil nitrogen content and decrease the C/N ratio, and improve soil water and thermal status, leading to a higher biomass yield. Therefore, the rational straw incorporation practice for improving biomass yield of winter wheat was the ALP treatment.

WUE of summer maize with the ALP treatment was higher than that with the CK treatment at the ten-leaf collar–tasseling stage in 2011–2013, indicating that the combined use of chemical fertilizers and straw incorporation increased the water use efficiency of biomass yield [24]. The LP treatment compared with the CK treatment decreased WUE of summer maize at the sowing–tasseling stage in 2013. This was because that the effect of crop straw plowed into the soil on soil water retention was negative at the early stages of crop growth and the water supply from deep soil layers was limited under the LP treatment as the soil capillary was partially cut off by crop straw. WUEs of winter wheat with the LP and ALP treatments were higher than that with the CK treatment from the tillering–jointing stage to the grain filling–maturity stage in 2011–2014. This was mainly because the combined use of crop straw plowed into the soil and N fertilization improved winter wheat biomass yield and presented suitable soil water-holding capacity, resulting in higher biomass water use efficiency during the three winter wheat seasons.

The ALP treatment increased TWUE of winter wheat by 4.1–22.0% compared with the CK treatment in 2011–2014, indicating that ammoniated straw with N fertilizer plowed into the soil could improve winter wheat biomass yield and increase biomass water use efficiency. The ALP treatment compared with the LP treatment increased TWUE of winter wheat by 3.1–7.0% in 2011–2014 and that of summer maize by 6.0% in 2012 and 7.0% in 2013, respectively, indicating that ammoniated straw could rapidly decompose, reduce soil water loss induced by long crop straw, and enhance biomass yield and biomass water use efficiency. The annual TWUEs with the ALP treatment were higher by 3.1–13.0% and 4.1–5.0% than that with the LP and CK treatments, respectively. Therefore, the rational straw incorporation practice for improving WUE was the ALP treatment, which could be used in the winter wheat–summer maize rotation system in the Loess Plateau of northwest China.

5. Conclusions

Straw mulching is not conducive to crop growth due to the slow decomposition rate of crop straw. Compared with the CK treatment, the ALP treatment improved summer maize biomass yield and winter wheat biomass yield at the jointing–maturity stage. The WUEs of winter wheat with the LP and ALP treatments were higher than that with the CK treatment from the tillering–jointing stage to the grain filling–maturity stage. The annual TWUEs with the ALP treatment were higher by 3.1–13.0% and 4.1–5.0% than that with the LP and CK treatments, respectively. Ammoniated crop straw with N fertilizer plowed into the soil can retain soil water in the 0–60 soil layer, increase biomass yield, and maintain biomass water use efficiency in the winter wheat–summer maize rotation in the Loess Plateau of Northwest China.

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