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Effects of Straw Input on the Yield and Water-Use Efficiency of Spring Maize in Film-Mulched Farmland

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Abstract: To provide a theoretical basis for the sustainable application of autumn mulching technology, we examined the effects of straw input on spring maize yield and water-use efficiency in film-mulched farmland. Based on the positioning tests of different mulching methods conducted in 2013, non-mulching (NM), spring mulching (SM), autumn mulching (AM), and autumn mulching combined with the return of straw (AMS) were selected in western Liaoning from 2018 to 2021. Spring maize yield, yield component factors, soil water content, and water-use efficiency under the four treatments were assessed. In each year, the AMS treatment significantly increased the maize yield, which was 48.22%, 9.33%, 30.66%, and 9.92%, and 11.78%, 7.71%, 12.86%, and 4.77% higher than that obtained after the SM and AM treatments, respectively. However, the harvest index was not significantly improved by AMS. AMS treatment significantly improved the precipitation utilization rate in all assessed years. Moreover, the crop water consumption was significantly increased by AMS treatment. Compared with the NM treatment, water-use efficiencies for economic and biological yield were also significantly improved. Thus, autumn mulching combined with straw-returning technology is an effective technical measure for improve spring maize yield and water-use efficiency in semi-arid areas of western Liaoning.

Keywords: returning straw to the field; mulching; spring maize (*Zea mays* L.); yield; water-use efficiency

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1. Introduction

Liaoning Province is one of the 13 major grain-producing areas in China, with an annual sown area of spring maize exceeding 2×10^6 ha, of which the northwestern region accounts for more than two-thirds of the total sown area, and annual yields exceed 75% of the total provincial output [1]. Consequently, ensuring stable maize yields in this region is an important guarantee for the food security of Liaoning Province [2]. Fuxin City, located in the northwest of the province, is a typical dry farming area [3], in which rainfall varies considerably and droughts are frequent. A typical climatic characteristic of this area is "there were nine droughts in ten years", which leads to the instability of maize yields and marked variability in the average annual yield per unit area [4].

In China, the application of film-mulching technology has been adopted in a wide range of areas, including North China, Northeast China, the Loess Plateau, and other regions characterized by different climatic and geographical conditions [5–7]. Given that the use of mulching film has the advantages of preserving soil moisture, increasing soil temperature, and increasing yield, mulching technology can contribute to significant improvements in spring maize yield and water-use efficiency (WUE), enhances the soil micro-ecological environment, and promotes increases in grain crude starch content and grain bulk weight [8]. With the temperature rising and the rainfall decreasing year by year, as a global climate-adaptive agricultural strategy, autumn film-mulching can effectively adapt to local climate change and show remarkable effects and potential in improving the stability and yield of crops and alleviating the impact of climate change [9]. Furthermore, returning straw to the field has the advantages of soil fertilization and increasing soil carbon content [10], both of which are important means of promoting water storage and soil moisture conservation. To some extent, the droughts associated with irregular annual precipitation can be alleviated [11], and the effective combination of mulching and returning straw can provide technical support for the improvement of regional grain production capacity and sustainable agricultural development [12].

The findings of numerous previous studies have provided evidence to indicate that mulching can contribute to improvements in rainfall capture, suppress soil water evaporation, and increase soil water storage, thereby enhancing WUE [13–15]. In addition, mulching can contribute to enhancing soil microbial activity, increase soil bacterial richness and diversity, accelerate the rate of soil mineralization, and enhance the soil water and nutrient absorptive capacities of spring maize roots, thus promoting increases in maize yield [16–19]. However, some studies have emphasized that the long-term application of autumn-mulching technology could alter the content of organic matter in the soil to a certain extent and destroy the soil structure, thereby reducing the yield of maize [20–22]. Returning straw to the field is an effective means of improving the physical and chemical properties of soil [23], with the findings of some studies indicating that incorporating residual crop material can significantly improve the soil structure, increase the proportion of large aggregates, increase soil organic matter content, replenish soil nutrients, such as nitrogen, phosphorus, and trace elements, and enhance land productivity [24]. In addition, the return of straw can also promote the transformation of small and medium soil particles to large water-stable aggregates, resulting in a significant increase in the proportion of large water-stable aggregates of large particle sizes [25]. These measures not only contribute to improving soil fertility but also enhance soil drought resistance [26]. However, a single return of straw will reduce ground temperature and affect straw decay, and if the straw is not fully decomposed, this could have detrimental effects regarding sowing quality, emergence, and crop growth [27,28]. Consequently, the effects of continuous long-term straw input on spring maize yield in film-mulched farmland warrant further study.

On the basis of the combined strategy of mulching and returning straw to the field to solve the problem of reductions in maize yield that may occur as a consequence of continuous mulch, previous research results have shown that mulching combined with the input of residual straw can promote significant increases in soil volume and the water content of the 0–50 cm soil layer, and also promotes increases in the water consumption of spring maize, which has notable advantages compared with a single return of straw to the field [29]. However, when using this approach, it has yet to be reported whether crop yield and WUE can be maintained under different rainfall patterns over many consecutive years.

On the basis of the findings of a positioning experiment conducted in 2013 in western Liaoning, China, in this study, we selected maize-cultivated land under different treatments for four consecutive years from 2018 to 2021 to examine the effects of straw input under different mulching conditions on temporal and spatial changes of soil moisture, maize growth and development, yield and yield component factors, and WUE. Our specific aims in this study were to examine the effects of the application of different farmland management measures coupled and integrated with spring maize production; to achieve the goals of water saving and increased production, high yields, and high efficiency; to identify more reasonable water-saving measures under an autumn-mulching planting mode; and to provide certain theoretical support for solving the problems of low WUE and low yield levels in a semi-arid region of western Liaoning.

2. Materials and Methods

2.1. Study Site Experimental Design

The study was performed at the Scientific Observing and Experiment Station of Fuxin Agro-Environment and Arable Land Conservation, Ministry of Agriculture, Fuxin county, Liaoning province, located in the south Khorchin area in Northeast China (42°11′ E, 121°70′ N, altitude 213 m). The climate of this region, a typical wind–sand semi-arid area, is a semi-arid monsoon continental type. From 1965 to 2017, the average annual temperature of the region was 8.1 °C, the average hours of sunshine from April to September was 1438.9 h, the accumulated temperature $\geq$ 10 was 3382 °C, the frost-free period was 183 days, the average evaporation was 1043.9 mm, and the average precipitation was 300–500 mm. The terrain of the experimental area is flat, and the soil in the experimental field is a calcic brown soil (sand 60.6%, silt 20.5%, clay 18.9%). The basic physical and chemical properties of the soil are as follows: soil bulk density, $1.35 \mathrm{g \cdot cm^{-3}}$; organic matter content, $15.36 \mathrm{~g \cdot kg^{-1}}$; total nitrogen, $0.90 \mathrm{~g \cdot kg^{-1}}$; total phosphorus, $0.76 \mathrm{~g \cdot kg^{-1}}$; total potassium, $28.46 \mathrm{~g \cdot kg^{-1}}$; available nitrogen, $101.12 \mathrm{~mg \cdot kg^{-1}}$; available phosphorus, $106.13 \mathrm{~mg \cdot kg^{-1}}$; and available potassium, $105.47 \mathrm{~mg \cdot kg^{-1}}$.

For the purposes of this study, we selected data collected over the 4 years from 2018 to 2021 for analysis. The average temperature and rainfall during the crop growth period in the experimental area in each year are shown in Figure 1. The rainfall during the growth periods of the years 2018 to 2021 were 296.1, 561.4, 458.4, and 548.5 mm, respectively. The rainfall in 2018 was lower than the average level recorded in previous years, whereas that in 2019 and 2021 was higher than the average level in previous years. Meteorological data were sourced from the automatic weather station (DL 16) at the Scientific Observing and Experiment Station of Fuxin Agro-Environment and Arable Land Conservation, Ministry of Agriculture.

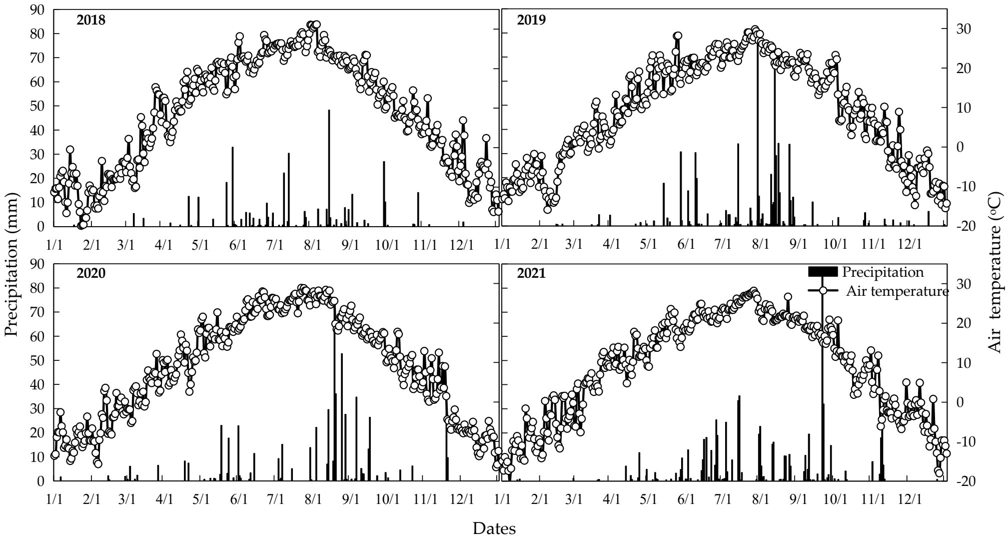

Figure 1. Rainfall and average temperature during the maize-growing period.

The maize variety assessed in this study was Jingke 968. The mulch for assessments was a typical polyethylene black mulch produced by Fuxin Plastics No. 2 Factory, with a thickness of 0.008 mm and a width of 1 m. The experiment was based on a completely randomized block design comprising the following four treatments: no mulching (NM); spring mulching (SM); autumn mulching (AM); and autumn straw mulching (AMS). Treatments were performed as three replicates in 50 $\mathrm{m^2}$ (5 m × 10 m) plots, each of which received the same fertilization according to the standards of phosphorus (150 kg $\mathrm{P_2O_5 \cdot ha^{-1}}$), potassium (75 kg $\mathrm{K_2O \cdot ha^{-1}}$), and nitrogen (240 kg $\mathrm{N \cdot ha^{-1}}$) fertilizers. The specific annual plot treatments were as follows. On October 1st, a small rototiller was used to eliminate stubble and prepare the land in a unified manner, with tillage to a depth of 20 cm. Following AM treatment in autumn, fertilizer was applied a single time, and the soil was covered with film after spraying acetochlor. For the SM treatment, prior to spring sowing, fertilizer was applied a single time, and the soil was covered with film after acetochlor spraying, whereas for the NM treatment, prior to spring sowing, fertilizer was applied a single time without film mulching, and acetochlor was sprayed after sowing. The length of each side of the mulch measures ten centimeters and is covered by soil in the mulch treatment. In each plot, 80% of the ground surface was covered. The planting approach in this study involved covering the two ridges with mulch. We established a planting density of 60,000 plants ha^{-1}, in which maize was planted in rows with an inter-row spacing of 0.5 m and inter-plant spacing of 0.33 m. The sowing period from 2018 to 2021 was 3 May, 6 May, 18 May, and 18 May, respectively, with corresponding harvesting on 28 September, 14 October, 23 September, and 24 September. None of the plots received supplementary irrigation; to prevent the effects of herbicides, we employed manual weeding. Disease and pest control were tailored to the specific conditions of the field.

2.2. Measurements

2.2.1. Yield and Its Components

After the harvesting of maize in each of the four study years, ten plants were randomly selected from each plot for yield measurements, and the moisture content was measured used a grain moisture tester (YT-L80). The values obtained from three replicate determinations were converted to values of yield per hectare. In addition, in each sample area, we randomly selected 15 consecutively planted maize plants to determine the selected yield composition factors, namely, cob length (cm), cob thickness (mm), grain row number per cob, number of grains per row, and 100-grain weight (g).

2.2.2. Biological Yield of the Population

During the harvest period, ten plants were randomly selected from each plot, and only above-ground biomass was taken as biological yield. After weighing and recording the fresh weights, the plants were placed in an electric thermostatic drying oven (DHG-9023A) at 105 °C for 60 min, and subsequently dried to a constant weight at 85 °C. Having thus determined the dry weights of plants, we calculated plant moisture contents.

Values for the harvest index of maize were determined using the following equation [30]:

$$HI = GY/BY \tag{1}$$

where HI is the crop harvest index, GY is the economic yield of crops (kg·ha^{-1}), and BY is the biological yield of crops (kg·ha^{-1}).

2.2.3. Soil Moisture Content

Using the soil drilling sampling drying method, in 2018, the seedling (24 April), jointing (26 June), filling (3 August), harvesting (1 October), 2019 seedling (28 April), jointing (7 July), filling (17 August), harvesting (17 October), 2020 seedling (24 May), jointing (23 July), filling stage (26 August), harvesting stage (23 September), seedling stage in 2021 (31 May), jointing stage (27 July), filling stage (27 August), harvesting stage (24 September), and soil moisture content of 0–100 cm was measured. The samples were collected at 10 cm intervals from the soil depth of 0–100 cm and repeated three times.

Soil water storage capacity was calculate using the following equation [30]:

$$W = 0.1 \times r \times v \times h \tag{2}$$

where W is soil water storage capacity, r is soil bulk density (g·cm^{-3}), v is the soil moisture content (%), and h is the soil depth (cm).

2.2.4. Precipitation-Use Efficiency during Growth Period

Precipitation-use efficiency (PUE) was calculated using the following equation [31]:

$$PUE = GY/R, \tag{3}$$

where PUE is the precipitation-use efficiency (kg·ha·mm^{-1}) during the growth period; GY is the kernel (economic) yield (kg·ha^{-1}); and R is the rainfall during the growth period (mm), values of which were recorded in the experimental area using an automatic weather station.

2.2.5. Crop Water Consumption

Crop water consumption was determine using the following equation [32]:

$$ET = P + U - R - F - \Delta W \tag{4}$$

where ET is crop water consumption (mm); P is precipitation during the crop growth period (mm); U is groundwater recharge (mm); R is the runoff (mm); F is soil water leakage (mm); ΔW is the change (mm) of soil water storage in the root layer after harvest and before sowing, with the soil water storage calculated based on the moisture content of the topmost 1 m soil layer. Given that the terrain of the experimental area is flat, the extents of surface runoff and soil water leakage were negligible. Conversely, given the deep-lying location of groundwater, generally tens of meters below the ground surface, the influence of the groundwater supplementation can be ignored. Accordingly, Equation (4) can be simplified as follows:

$$ET = P - \Delta W \tag{5}$$

2.2.6. Water-Use Efficiency

Water-use efficiency can be determined using the following equations [33]:

$$WUE_{gy} = GY/ET \tag{6}$$

$$WUE_{by} = BY/ET, \tag{7}$$

where WUE_{gy} is the water-use efficiency of grain (economic) yield (kg·ha^{-1}·mm^{-1}) and WUE_{by} is the water-use efficiency of biological yield (kg·ha^{-1}·mm^{-1}).

2.3. Statistical Analysis

The experimental data were collated and analyzed using Excel 2023 and plotted using Excel 2023 and Origin 2022. For multiple comparisons, the data were statistically analyzed using ANOVA in conjunction with Tukey's method ($p < 0.05$) performed using SPSS17.0 software.

3. Results

3.1. Effects of Straw Input on Yield and Harvest Index of Film-Mulched Spring Maize

3.1.1. Effects of Different Treatments on Yield

By comparing the yields of maize obtained in different years under different treatments (Figure 2), we found that the average annual yield of spring maize was between 6810 and 15,168.5 kg·ha^{-1}, with a large inter-annual difference. Specifically, we recorded the highest yield in 2021, followed by 2019, 2020, and 2018 in that order. In terms of different treatments, the yield values in each year declined in the order AMS > AM $\geq$ SM > NM (AMS $\geq$ AM > SM $\geq$ NM in 2018). From 2019 to 2021, AMS was found to be significantly more effective in promoting yield than the other treatments ($p < 0.05$), whereas NM was significantly less effective than the other treatments ($p < 0.05$). From 2018 to 2021, the AMS treatment yield increased by 106.39%, 25.87%, 54.77%, and 19.64% compared to the NM treatment; by 48.22%, 9.33%, 30.66%, and 9.92% compared to the SM treatment; and by 11.78%, 7.71%, 12.86%, and 4.77% compared to the AM treatment.

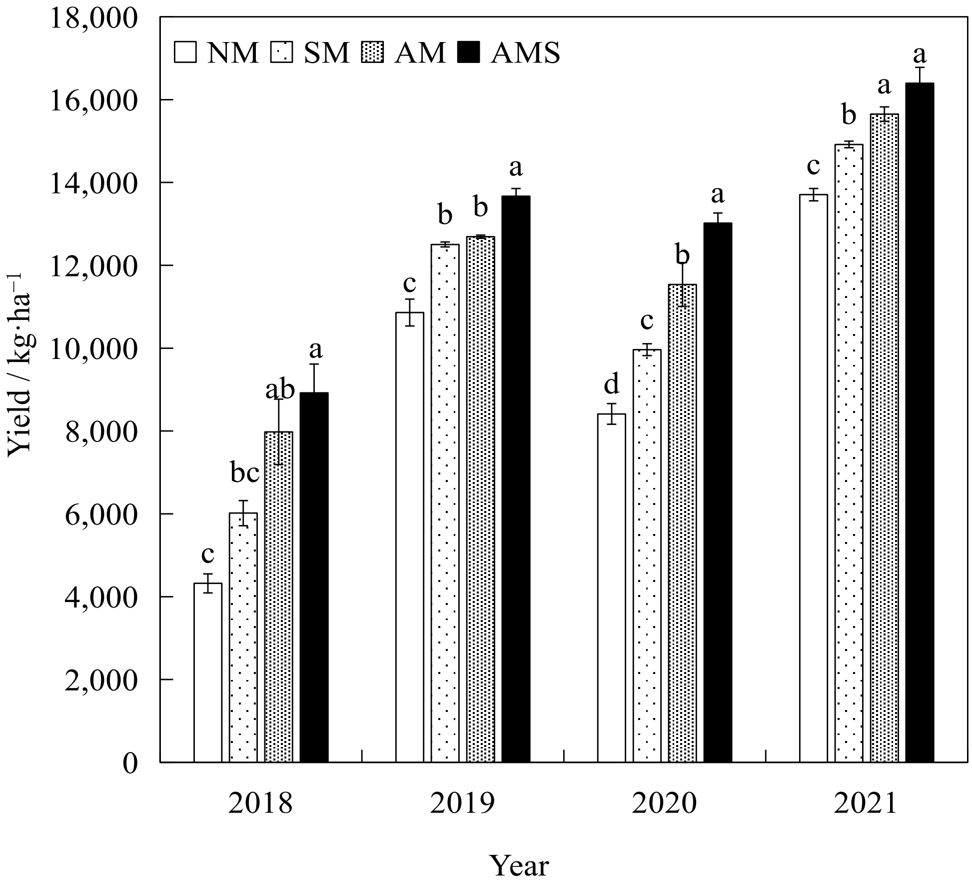

Figure 2. Effects of continuous film mulching combined with straw returning on spring maize yield in different years. A different letter within a column for treatments is significantly different at the $p < 0.05$. NM, no mulching; SM, spring mulching; AM, autumn mulching; AMS, autumn straw mulching.

3.1.2. Influence of Different Treatments on Yield Components

As can be seen from the yield components shown in Table 1, from 2018 to 2021, there were significant differences in cob length between different treatments ($p < 0.05$), no significant difference between AMS and AM treatments ($p > 0.05$) or between AM and SM treatments ($p > 0.05$). Except for 2019, the AMS treatment consistently resulted in significantly longer cob length compared to the SM treatment ($p < 0.05$). Regarding cob thickness, there was little difference between treatments, no significant difference between AMS, AM, and SM treatments ($p > 0.05$). However, in 2018, both AMS and AM treatments resulted in significantly greater cob thickness compared to the NM treatment ($p < 0.05$). The results would thus tend to indicate that in dry years, autumn mulching combined with the return of straw would not have any marked effects in terms of promoting an increase in cob thickness compared with a single autumn mulching. The pattern of variation observed for cob diameter in each year tended to be similar to that of cob length.

With regard to the grain row number per cob, we detected significant inter-treatment differences only in 2018, when rainfall was low, with the AMS and AM treatments being found to be significantly more effective than the NM treatment ($p < 0.05$). Contrastingly, no significant differences were detected among treatments in the other 3 years ($p > 0.05$), thereby indicating that the grain row number per cob changed little in response to treatment, and that higher rainfall is less conducive in contributing to an increase in the grain row number per cob. In terms of number of grains per row, although the AMS, AM, and SM treatments differed little in their respective effects ($p > 0.05$), they were significantly more effective than the NM treatment ($p < 0.05$). Only in 2021 was there no significant difference among the four treatments ($p > 0.05$). The average number of grains per row in 2021 was

38.17, which was higher than the values 32.23 and 30.47 obtained in 2020 and 2018, whereas the average row grain number in 2019 reached a maximum value of 38.52, indicating that, in contrast to the spike in number of grains per row, higher rainfall had a certain promoting effect with respect to increasing the row grain number.

Table 1. Effects of continuous film mulching combined with straw returning on yield composition factors.

Year	Treatment	Cob Length/cm	Cob Thickness /mm	Grain Row Number per Cob	Number of Grains per Row	100-Grain Weight/g
2018	NM	11.43 ± 0.50 c	31.71 ± 2.58 b	13.60 ± 0.35 b	23.80 ± 1.33 b	24.53 ± 1.34 b
	SM	13.93 ± 0.33 b	42.76 ± 0.41 ab	14.80 ± 0.38 ab	31.80 ± 0.93 a	24.78 ± 0.49 b
	AM	14.60 ± 0.51 ab	43.69 ± 0.82 a	14.93 ± 0.33 ab	31.53 ± 1.31 a	30.46 ± 2.43 ab
	AMS	15.67 ± 0.39 a	37.90 ± 2.40 a	15.07 ± 0.43 a	34.73 ± 1.09 a	34.30 ± 1.14 a
2019	NM	16.30 ± 0.41 b	50.01 ± 0.40 a	14.27 ± 0.33 a	36.07 ± 1.28 b	35.22 ± 0.66 b
	SM	17.90 ± 0.32 a	49.95 ± 0.44 a	14.13 ± 0.36 a	39.67 ± 1.04 ab	37.81 ± 0.38 ab
	AM	17.70 ± 0.28 a	51.57 ± 0.54 a	14.80 ± 0.26 a	39.13 ± 0.68 ab	37.60 ± 0.99 ab
	AMS	18.00 ± 0.22 a	51.18 ± 0.39 a	14.80 ± 0.33 a	39.20 ± 0.74 a	40.80 ± 0.70 a
2020	NM	15.57 ± 0.54 b	45.36 ± 1.35 b	14.80 ± 0.51 a	29.20 ± 1.52 a	35.96 ± 0.34 a
	SM	15.53 ± 0.74 b	47.10 ± 0.60 ab	15.47 ± 0.41 a	31.47 ± 1.71 a	35.53 ± 0.85 a
	AM	17.33 ± 0.36 ab	47.60 ± 2.58 ab	15.73 ± 0.27 a	34.60 ± 1.42 a	35.39 ± 1.15 a
	AMS	17.60 ± 0.41 a	49.81 ± 0.74 a	15.73 ± 0.27 a	33.67 ± 1.30 a	37.11 ± 1.99 a
2021	NM	17.57 ± 0.36 c	53.84 ± 0.52 b	16.40 ± 0.56 a	35.80 ± 0.83 a	40.31 ± 0.38 a
	SM	18.03 ± 0.26 bc	54.82 ± 0.41 ab	16.53 ± 0.31 a	36.87 ± 0.73 a	46.25 ± 3.33 a
	AM	19.30 ± 0.20 ab	55.99 ± 0.36 ab	17.33 ± 0.37 a	37.47 ± 1.08 a	43.43 ± 0.37 a
	AMS	19.60 ± 0.34 a	55.29 ± 0.35 a	17.07 ± 0.38 a	38.53 ± 1.15 a	43.75 ± 1.31 a
p-value	Treatment (T)	0.003	0.049	0.056	0.006	0.000
	Year (Y)	0.000	0.000	0.000	0.001	0.000
	T × Y	0.270	0.285	0.702	0.221	0.010

Data are mean ± SE. Values followed by a different letter within a column for treatments are significantly different at the $p < 0.05$.

In terms of hundred-grain weight, in both 2018 and 2019, we detected the trend of AMS ≥ AM > SM ≥ NM with respect to treatment efficacy, indicating that the AMS treatment can promote significant increases in the hundred-grain weight during periods with both high and low levels of precipitation. However, in both 2020 and 2021, we detected no significant difference among treatments ($p > 0.05$). Nevertheless, in years with moderate rainfall, AMS treatment can promote significant increases in the hundred-grain weight. Different treatments were found to have little influence on the grain weight. For the years 2018, 2019, 2020, and 2021, we recorded average grain weights of 28.52, 37.86, 36.00, and 43.44 g, respectively, indicating that neither high nor low amounts of rainfall are conducive to achieving peak grain weight. High rainfall could increase the 100-grain weight of spring maize to a certain extent, but higher rainfall might reduce the 100-grain weight.

3.1.3. Effects of Different Treatments on Biological Yield and Harvest Index

Our analyses of maize biological yield and harvest index revealed that straw input had a significant influence on the effect of continuous film mulching on spring maize population biological yield ($p < 0.05$) (Figure 3). In different years, the overall performance of the different treatments in this regard was AMS > AM ≥ SM > NM. Compared with the NM treatment, AMS treatment contributed to yield increases of 106.39%, 25.87%, 54.77%, and 19.64%, in the years 2018, 2019, 2020, and 2021, respectively. Contrastingly, with respect to harvest index, for each of the assessed years, we detected no significant differences in the four treatments ($p > 0.05$), with values being maintained between 0.44 and 0.54 and showing little variation.

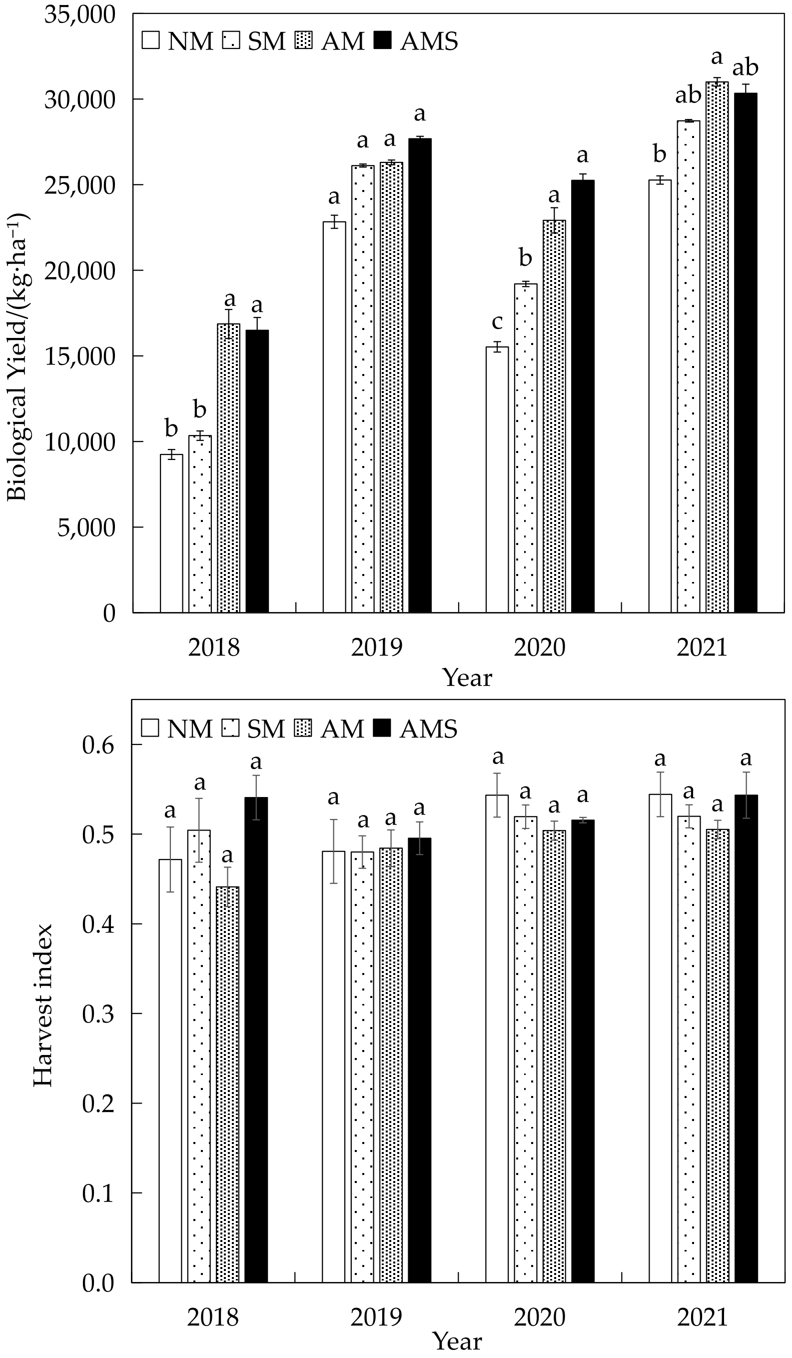

Figure 3. Effects of straw returning and different mulching techniques on biological yield and harvest index of maize. A different letter within a column for treatments is significantly different at the $p < 0.05$. NM, no mulching; SM, spring mulching; AM, autumn mulching; AMS, autumn straw mulching.

3.1.4. Correlation Analysis of Yield Components

The findings of our correlation analysis (Figure 4) indicated that there was an extremely significant positive correlation between spring maize yield (Y) and each of the assessed yield component factors ($p < 0.01$), with the strength of the correlation declining in the following order: 100-grain weight (X5) > cob thickness (X2) > cob length (X1) > number of grains per row (X4) > grain row number per cob (X3). Moreover, we also detected extremely significant positive correlations among the components of spring maize yield ($p < 0.01$), among which the strongest correlation was between 100-grain weight and yield, with a correlation coefficient reaching 0.90 ($p < 0.01$), and the weakest correlation being between number of grains per row and the grain row number per cob, for which the correlation coefficient was only 0.47.

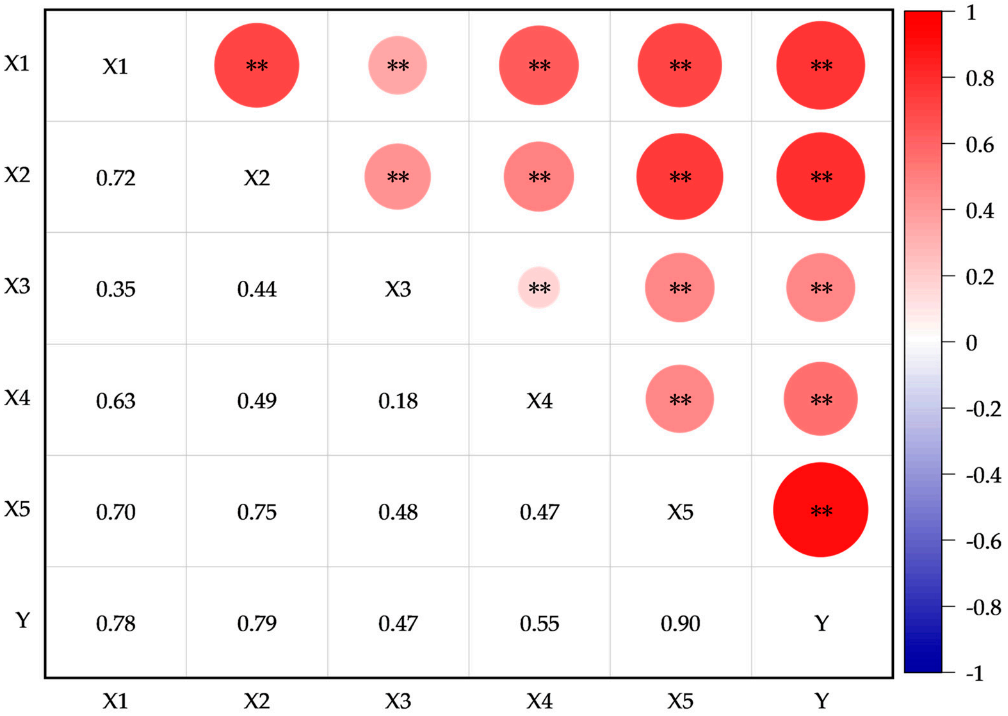

Figure 4. Correlation analysis of spring maize yield components. In the legend, X1 represents cob length, X2 represents cob thickness, X3 represents grain row number per cob, X4 represents number of grains per row, and X5 represents 100-grain weight. ** means significant difference in treatment at $p < 0.01$, same as below.

3.1.5. Path Analysis among Yield Components

In path analysis, correlation coefficient values are categorized as being indicative of direct or indirect action, that is, direct path and indirect path coefficients, to further clarify the direct and indirect effects of each factor on yield. The direct path coefficient of a factor is the standard coefficient, whereas an indirect path coefficient of a factor indirectly influences yield via another factor, which is equal to the direct path coefficient multiplied by the correlation coefficient of one factor to another factor. For path analysis in this study, we took yield component factors as independent variables and spring maize yield as the dependent variables.

For each of the five assessed yield components (Table 2), we detected an extremely significant positive correlation with yield ($p < 0.01$), among which 100-grain weight (X5) had a significant direct effect on spring maize yield (Y) (0.63), whereas the other yield components showed no direct action with yield ($p > 0.05$). The direct effect of each yield component on yield was as follows: 100-grain weight (X5) > cob length (X1) > cob thickness (X2) > number of grains per row (X4) > grain row number per cob (X3). This indicates that 100-grain weight had a greater direct effect on yield, followed by cob length and cob thickness, and grain row number per cob and number of grains per row, which had less significant effects. Although the correlation coefficients of the other yield components were very significant ($p < 0.01$), most of these effects could be attributed to the effects of 100-grain weight on yield (X5-Y).

Table 2. Path analysis of spring maize yield components.

Factors	Simple Correlation Coefficient with Y	Path Coefficient (Direct Action)	Indirect Path Coefficient				
			X1-Y	X2-Y	X3-Y	X4-Y	X5-Y
X1	0.780 **	0.168	-	0.120	0.001	0.047	0.444
X2	0.786 **	0.167	0.121	-	0.001	0.025	0.472
X3	0.469 **	0.002	0.070	0.091	-	0.005	0.302
X4	0.545 **	0.064	0.122	0.065	0.001	-	0.294
X5	0.904 **	0.630 **	0.118	0.125	0.001	0.030	-

** means significant difference in treatment at $p < 0.01$.

3.2. Effects of Combined Straw Input and Continuous Film Mulching on Soil Moisture Content

The levels of soil moisture reflect the water-holding and water supply capacities of soil. The results obtained for the water content of soil subjected to the four assessed treatments during the period from 2018 and 2021 are shown in Figure 5. In general, the different soil layers of plots that had received mulch treatment at all growth stages had higher moisture contents, and the average moisture content of soils under the different treatments could be ordered as AMS > AM > SM > NM, and was particularly evident at the seedling stage. Both the AMS and AM treatments were found to promote significant increases in soil moisture content at the seedling stage ($p < 0.05$), with higher moisture levels being recorded in the shallower layer of soil receiving the AMS treatment. These findings provide evidence to indicate that the incorporation of straw within the soil loosened the soil structure and thereby increased the capacity for rainwater infiltration, thus contributing to an increase in the content soil moisture. Contrastingly, we detected relatively little difference in moisture content at the seedling stage in soils that had received the SM and NM treatments. On the whole, with the exception of the values obtained in 2021, there was relatively little variation in soil moisture contents at the seedling stage, with ranges of between 12.31% and 21.05%, 9.27% and 20.42, 10.14% and 28.35%, and 11.28% and 39.21%, being recorded in 2018, 2019, 2020, and 2021, respectively. The jointing stage is the key period for maize growth, and given the concomitant growth of roots during this period, there tends to be a high consumption of soil water. We detected similar change trends in each of the 4 years assessed in this study, with these changes being more evident in soil at depths below 50 cm. Moreover, in soil receiving the NM treatment, we detected a larger range of change in 2019 and 2020, indicating that non-mulched soil is characterized by a more pronounced response to changes in moisture content. The measured ranges for the years 2018, 2019, 2020, and 2021 were 27.29–39.14%, 22.81–42.81%, 6.26–44.73%, and 21.50–38.58%, respectively. At the filling stage, we detected annual differences in the amplitude of variation, although the overall moisture content was higher. The trend of soil water variation at the mature stage was found to be similar to that at the filling stage, which reflects the decline in plant demand for water during this period.

3.3. Effects of Combined Straw Input and Continuous Film Mulching on Plant Water-Use Efficiency

3.3.1. Precipitation-Use Efficiency

Our analysis of PUE at the growth stage revealed significant differences among the four assessed treatments ($p < 0.05$), with the extent of the effects in each year being ordered as follows AMS > AM > SM > NM (Figure 6). Over the 4 years of the study, the highest average PUE obtained during the growth period was recorded in 2018 in soil that had received the AMS treatment, reaching a value of 30.12 $kg \cdot ha^{-1} \cdot mm^{-1}$. The lowest PUE (14.60 $kg \cdot ha^{-1} \cdot mm^{-1}$) was recorded in the same year in soil receiving the NM treatment. In response to the SM treatment in the same year, PUE values reached a high of only 20.32 $kg \cdot ha^{-1} \cdot mm^{-1}$, which did not differ significantly from the value obtained under the NM treatment ($p > 0.05$). These findings thus indicate that spring mulching is an inefficient means of meeting the water required for plant growth during exceptionally dry years, which influences the annual PUE.

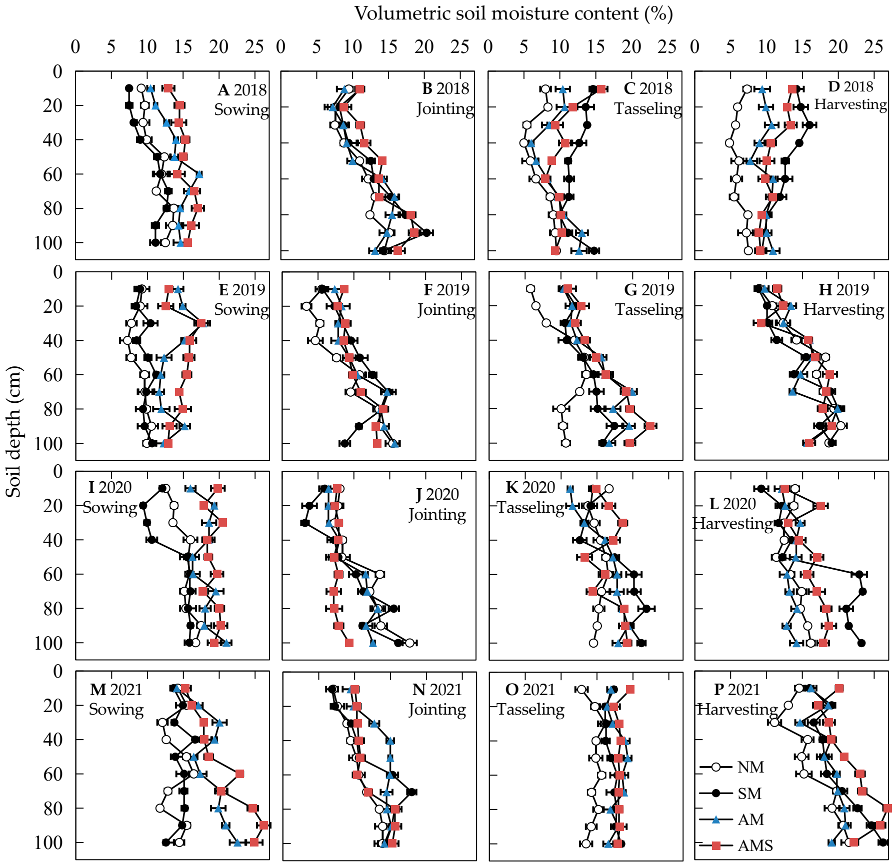

Figure 5. Dynamic changes of soil moisture content in 0~100 cm stratified layers of spring maize during different growth periods under continuous film mulching combined with straw returning.

3.3.2. Crop Water-Use Efficiency

We found that the effects of the combined application of straw input and continuous film mulching on crop water consumption and crop water-use efficiency differed in years with notably different amounts of rainfall (Table 3). In terms of crop water consumption, in 2018, the highest value was recorded in soil receiving the NM treatment, which was 37.43% higher than that recorded for the SM-treated soil. Contrastingly, in 2019, the highest crop water consumption was detected in plots receiving the combined straw input/mulching treatment (ordered as AMS > AM > SM > NM), with this value being 17.81% higher than that obtained in the NM treatment. In both 2020 and 2021, the performance of treatments could be ordered as AM > AMS > NM > SM, with the highest value achieved under the AM treatment as 26.96%, which is 15.23% higher than that obtained under the SM treatment, respectively. In terms of the WUE of biological yield, in each of the 4 years, the rate of utilization was lowest in plots receiving the NM treatment, whereas rates were highest in the AMS- and AM-treated plots in 2018 and 2020, and in the SM-treated plots in 2019 and 2021. Compared with the NM treatments, the highest increases in WUE in 2018, 2019, 2020, and 2021 were 110.77%, 8.57%, 55.49%, and 22.35%, respectively. The results obtained for the WUE of economic yield were similar to those recorded for biological yield, with the exception that the values obtained under the NM treatment were significantly lower than those obtained under other treatments ($p < 0.05$), and we detected no significant differences among other treatments ($p > 0.05$). Compared with the lowest values, the highest rates of utilization increased by 113.98%, 7.96%, 47.82%, and 17.04% in 2018, 2019, 2020, and 2021, respectively.

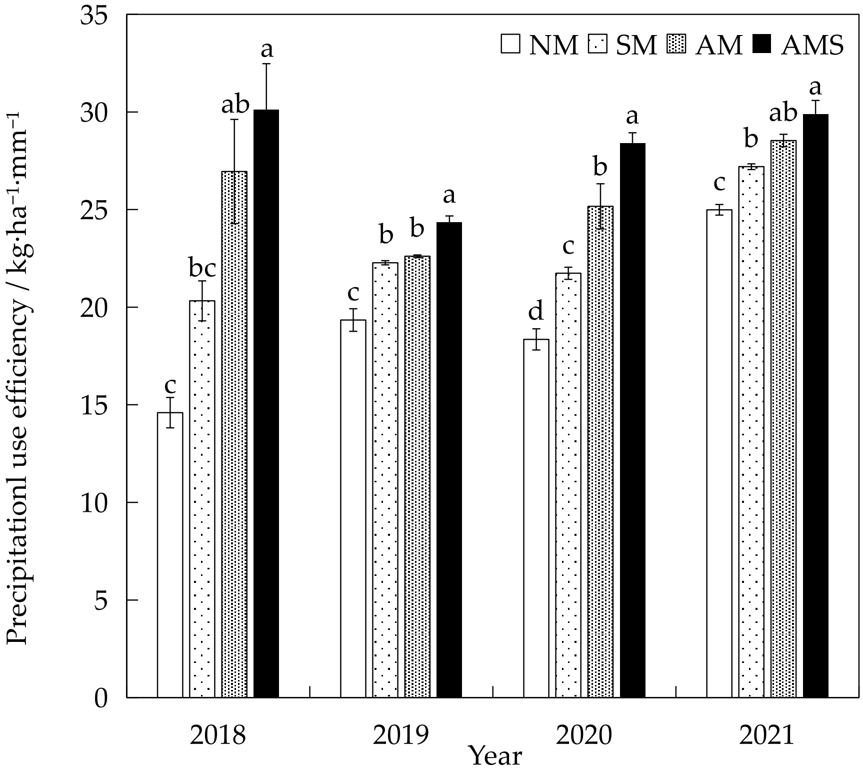

Figure 6. Effects of continuous film mulching combined with straw returning on precipitation-use efficiency during the growth period. A different letter within a column for treatments is significantly different at the $p < 0.05$. NM, no mulching; SM, spring mulching; AM, autumn mulching; AMS, autumn straw mulching.

Table 3. Effects of continuous film mulching combined with straw returning on water consumption and water-use efficiency of maize.

Year	**Treatment**	**Rainfall in Growth Period/mm**	**Crop Water Consumption/mm**	**Biological Yield Water-Use Efficiency/(kg·ha^{-1}·mm^{-1})**	**Yield Water-Use Efficiency/ (kg·ha^{-1}·mm^{-1})**
2018	NM	296.1	364.26 ± 12.47 a	25.53 ± 2.74 b	11.93 ± 1.02 b
	SM		265.05 ± 10.42 b	39.03 ± 0.07 ab	22.86 ± 2.03 a
	AM		323.4 ± 28.7 ab	53.81 ± 9.37 a	25.54 ± 4.93 a
	AMS		358.87 ± 12.1 a	46.29 ± 4.77 ab	25.02 ± 2.65 a
2019	NM	561.4	466.61 ± 14.81 b	48.96 ± 3.65 a	23.35 ± 1.34 a
	SM		497.36 ± 11.58 ab	52.5 ± 1.1 a	25.17 ± 0.71 a
	AM		544.71 ± 9.49 a	48.36 ± 2.66 a	23.32 ± 0.47 a
	AMS		549.74 ± 11.26 a	50.5 ± 3.42 a	24.9 ± 0.83 a
2020	NM	458.4	474.75 ± 9.78 b	32.73 ± 1.44 b	17.75 ± 0.86 c
	SM		411.82 ± 9.05 c	46.7 ± 1.87 a	24.23 ± 0.87 ab
	AM		522.85 ± 10.24 a	43.95 ± 3.15 a	22.12 ± 1.45 b
	AMS		496.84 ± 9.39 ab	50.89 ± 1.63 a	26.24 ± 0.97 a
2021	NM	548.5	514.02 ± 13.12 ab	49.19 ± 1.76 b	26.71 ± 0.97 b
	SM		477.82 ± 11.24 b	60.18 ± 1.64 a	31.26 ± 0.92 a
	AM		550.59 ± 9.48 a	56.38 ± 2.04 ab	28.46 ± 0.8 ab
	AMS		531.17 ± 12.19 a	57.34 ± 4.7 ab	30.93 ± 1.41 a
p-value	Treatment (T)	-	0.000	0.000	0.000
	Year (Y)		0.000	0.000	0.000
	T×Y		0.001	0.021	0.031

Data are mean ± SE. Values followed by a different letter within a column for treatments are significantly different at the $p < 0.05$.

3.3.3. Yield and Water-Use Efficiency

To clarify the relationship between yield and WUE in the Fuxin region, we performed regression analysis with crop economic yield WUE and crop biological yield WUE as the y coordinates and economic yield as the x coordinates. The linear regression equations obtained are shown in Figure 7. With the exception of 2020, the correlation between the WUE of economic yield and economic yield was stronger than that between the WUE of biological yield and economic yield. For the years 2018, 2019, 2020, and 2021, we obtained R^2 values of 0.778, 0.2607, 0.686, and 0.448, respectively, for the correlations between economic yield and the WUE of economic yield, and values of 0.7449, 0.0768, 0.7211, and 0.3777, respectively, for the correlations between economic yield and the WUE of biological yield.

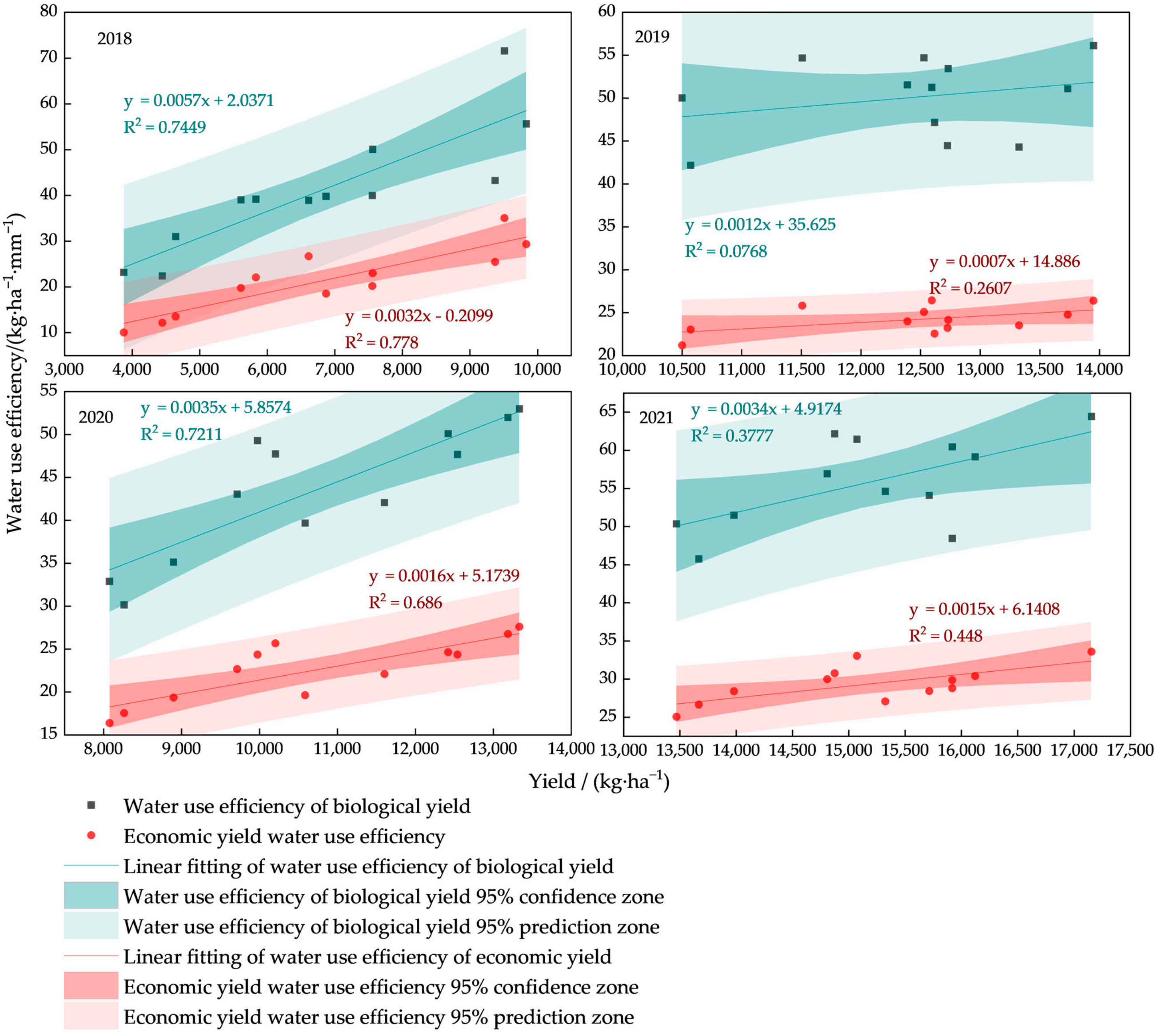

Figure 7. Relationship between yield and water-use efficiency.

4. Discussion

4.1. Effects of Different Treatments on Crop Yield, Yield Composition, and Harvest Index

Increases in crop yield and total biological yield serve as important indices for assessing the quality of farmland management measures, and the economic yield of maize varies significantly among different returning years, indicating that measures entailing the incorporation of residual straw can contribute to improvements in the economic yield of maize and that these are positively correlated with the returning years [34]. In the semi-arid areas of northwest China, it has been demonstrated that the continuous application of autumn mulching can promote increases in grain yield between 30% and 107% and increases in biological yield between 37% and 69% compared with non-mulched maize [35]. Consistently, in the present study, we found that the continuous autumn mulching with straw promoted significant increases in the yields of spring maize ($p < 0.05$). Moreover, analysis of the results obtained over four consecutive years from 2018 to 2021 revealed annual differences in the performance of the same treatments, which could be attributed to inter-annual variation in soil moisture and temperature. Nevertheless, in most of the assessed growing seasons, autumn-mulching treatment with continuous straw input was found to improve yield components, such as cob length and cob thickness, to certain extents, and promote significant increases in yield ($p < 0.05$). These findings are consistent with those reported in numerous previous studies. For example. Tan et al. [36] found that under conditions of returning straw to the field and mulching, yield was increased by 69.36% compared with the control treatment, whereas Liu et al. [37] have shown that compared with non-mulching, returning straw to the field under mulching conditions could significantly increase maize yield. Moreover, similar to our findings in the present study, it has been demonstrated that the yields of maize obtained in response to autumn-mulching maize were higher than those obtained with spring mulching [2,7]. Unlike the present study, relatively few previous studies have assessed the effects of autumn-mulching treatments based on the continuous return of straw over multiple consecutive years. We found that compared with spring mulching, autumn mulching contributed to yield increases of 32.60%, 1.50%, 15.77%, and 4.92% in the years 2018, 2019, 2020, and 2021, respectively. This indicates that in dry years, such as 2018, compared with spring mulching, autumn-mulching treatments can promote significant increases in yield, thus indicating that autumn film-mulching makes a valuable contribution to addressing the problem of irregular patterns of inter-annual precipitation. Similar to drought conditions, years with high rainfall also have a certain effect on yield.

Compared with AM treatment, in the years 2018, 2019, 2020, and 2021, we obtained yield increases of 11.78%, 7.71%, 12.86%, and 4.77%, respectively, in plots receiving the AMS treatment, thereby indicating that autumn mulching combined with the return of straw can contribute to promoting yields in years with differing amounts of annual rainfall, particularly in dry years, and is a more effective management measure for improving the yield of local spring maize. The combined application of residual straw and nitrogen fertilizer has been shown in several studies to enhance crop yield by promoting increases in the numbers of spikelet per spike and the weight of 100 grains [38]. Our analyses of yield components in this study revealed that the effects of treatments on 100-grain weights would influence the final yield. Moreover, we identified certain differences in the change trends of the harvest index in different years. Specifically, whereas the harvest index values recorded in plots receiving the NM and SM treatment were characterized by an overall upward trend from 2018 to 2021, the harvest index in plots receiving the AM and AMS treatments showed a slight downward trend, thereby indicating a certain inter-annual variation in the influence of different mulching methods on the harvest index. We speculate that these differences could reflect differences in rainfall patterns, which accordingly warrants further investigation. In addition, our findings of a relatively higher biological yield, but lower harvest index, in response to the AM treatment in a relatively dry year (2018) indicates that although continuous autumn mulching in a dry year can promote increases in the biological yield of spring maize, it does not necessarily promote an increase in economic yield, whereas in plots receiving straw input and continuous autumn mulching, the harvest index remains relatively stable. These findings thus provide evidence to indicate that straw input can more effectively coordinate the growth of plants under conditions of continuous autumn mulching, thereby contributing to increases in production and income.

4.2. Effects of Different Treatments on Soil Water and Water-Use Efficiency

At present, the global research trend of straw coverage mainly focuses on exploring its application in climate-adaptive agriculture strategy, especially in tackling climate change and improving agricultural sustainability [39,40]. As a conservation tillage measure, straw covering has multiple ecological benefits, including improving soil physical properties, regulating soil hydrothermal conditions, increasing soil organic matter content, and reducing greenhouse gas emissions [41,42]. A large number of studies have shown that returning straw to the field can contribute to an enhancement of soil water storage capacity and WUE [1,18,43]. By improving soil water storage capacity, the input of straw can ensure a sufficient water supply during the critical period of crop water storage, alleviate the discrepancy between water supply and the demand of crops in drylands, and improve crop yield and WUE. Our comparison of research data obtained over the period from 2018 to 2021 revealed that straw input for continuous autumn mulching could facilitate the efficient exploitation of precipitation during the crop growth period and enhance the PUE of crops. The utilization of straw as continuous autumn mulching generally contributes to a substantial enhancement in PUE across the majority of years [2]. In the present study, we found that the PUE of maize in plots receiving the AMS and AM treatments was significantly higher than that of maize in the SM- and NM-treated plots in 2018 and 2020, which were years characterized by low rainfall, thereby indicating that inter-annual differences in rainfall patterns have a considerable influence on the rates at which plants utilize water. Under drought conditions, water conservation and seedling promotion at the seedling stage can significantly improve the rate of water utilization of plants throughout the year, and can thereby contribute to ensuring stable plant yield in drought years. Under conditions of more abundant precipitation, such as those characterizing the years 2019 and 2021, we observed certain differences in trends, indicating that straw input has an equally significant impact on precipitation utilization in soils receiving continuous autumn mulching, although we detected little difference between the assessed mulching technologies under these conditions. In addition, we established that whereas in the year with low precipitation, water consumption was highest in plots receiving the AMS treatment, in the year with moderate precipitation, water consumption was highest in plots receiving the AM treatment in the absence of the return of straw. In the year with high precipitation, we detected little difference in water consumption in plots receiving the AMS and AM treatments, whereas regardless of precipitation levels, the consumption of water tended to be significantly lower in the SM-treated plots.

Our findings in this study thus revealed that the implementation of mulching and straw-returning practices contributed to increases in plant water consumption. Compared with traditional cultivation methods, the use of mulching has been demonstrated to promote a 5.72% increase in water consumption, whereas employing common mulching techniques resulted in a 2.54% increase [44]. On the basis of our analyses of data collected over four consecutive years, we found that spring mulching has the effect of reducing water consumption to a certain extent, whereas autumn mulching can promote certain increases in the consumption of water. Although in years with high rainfall, we found that AMS treatment contributed to only a limited improvement in crop WUE, in years characterized by low or normal levels of precipitation, the combined application of autumn mulching and straw input promoted significant increases in crop water consumption. We speculate that these effects could be attributable to the fact that returning straw to the field augments the volume of mulch at the soil surface. Although this contributes to the retention of soil water, it may also lead to reductions in soil temperature at night, thereby promoting an increase in the water consumption of crops, and also a significant improvement in the WUE of crops, which in turn contributes to high and stable crop yields. However, in contrast to our findings in this study, the findings of some previous studies have indicated that straw mulching can have the effect of reducing plant water consumption [45], which we suspect could be associated with differences in annual rainfall patterns, different soil textures, or different climatic environments. Verifying these assumptions will necessitate further research.

4.3. Relationships between Rainfall, Soil Moisture, and Yield in Different Years

As a typical dry farming area, the Fuxin region has insufficient irrigation resources and a deep-lying groundwater level. Consequently, farmers are generally reliant on natural precipitation to provide most of the water required for plant growth. Our observations of soil water content and crop yield clearly indicate that the soil water content fluctuates considerably according to the annual precipitation, with levels typically being low in years with low rainfall and increasing significantly when the levels of precipitation are high. This point has reached similar conclusions in many studies [46,47]. Accordingly, yields tend to fluctuate considerably in response to rainfall. On the basis of our analysis of the relationship between yield and WUE, we found that the yield of spring maize planted in the Fuxin area from 2018 to 2021 increased with an increase in WUE. This was particularly evident in 2018 and 2020, which indicates that the association between yield and WUE tends to be stronger in drier years and that currently, enhancing WUE remains an important approach for increasing the yield of maize in the Fuxin region. However, we have only analyzed the yield and WUE in this region over six to nine consecutive years, with annual rainfalls ranging from 296.1 to 561.4 mm. However, if precipitation is below 296.1mm or exceeds 561.4mm, further research is needed to determine its impact on deep-level desiccation, soil nutrient content, and other indicators.

5. Conclusions

Compared with traditional mulching methods, continuous autumn mulching with straw input for multiple consecutive years can contribute to significant increases in the yield of spring maize, along with significant improvements in the precipitation utilization rate, increases in the water consumption of crops, and a significant enhancement of water-use efficiency. In response to treatments combining continuous autumn mulching with straw input, we obtained a relatively stable harvest index, indicating that the input of straw can promote a more effective coordination of plant growth, thereby contributing to increases in production and income. Moreover, we found that in relatively dry years, the input of straw under conditions of continuous autumn mulching has a more evident effect in terms of enhancing yield and other indicators, thereby indicating that this management approach is more suitable for application in areas characterized by a low annual rainfall and those that experience an irregular distribution of annual rainfall.

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