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Beneficial Effects on Winter Wheat Production of the Application of Legume Green Manure during the Fallow Period

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Abstract: Legume green manure (LGM) is an excellent organic amendment conducive to soil quality and nutrient cycling; however, the use of LGM was once repealed in the rain-fed agriculture of northern China. The objective was to investigate the effects that planting LGM would bring and whether it would affect other fertilization regimes regarding the productivity and water and nutrient use efficiencies of succeeding crops. A short-term (2016–2019) field experiment was established with a split-plot design in the Loess Plateau of China, which included ten treatments consisting of two planting systems (main treatments)—conventional winter wheat monoculture (G0) and planting and incorporating LGM followed by winter wheat planting (G)—and five fertilization regimes (sub-treatments)—no fertilization (CK), basal fertilization with chemicals N, P and K (NPK), basal fertilization plus wheat straw return (NPK + S), basal fertilization plus farmyard manure application (NPK + M), and basal fertilization plus wheat straw return plus farmyard manure application (NPK + S + M). The results demonstrated that compared with G0, the G did not remarkably affect the total water consumption (WC) and water use efficiency (WUE) across the three trial wheat seasons. Specifically, during the third wheat season, the winter wheat yield of G increased by 7.5% more than that of G0 ($p < 0.05$). G primarily increased the N concentration in winter wheat and universally increased the uptake of N, P and K by 18.8%, 11.7% and 18.8%, respectively. The apparent use efficiencies (AUEs) of chemicals N, P and K under G were 88.0%, 102% and 93.2% higher than those under G0 ($p < 0.05$). In contrast, the wheat yields of NPK, NPK + S, NPK + M and NPK + S + M were 14.3%, 22.2%, 26.4% and 19.5%, respectively, higher than those of CK. The WC and WUE increased under NPK, NPK + S, NPK + M and NPK + S + M relative to the CK ($p < 0.05$). Compared with CK, the NPK, NPK + S, NPK + M and NPK + S + M primarily increased the N concentration in winter wheat and universally increased the uptake of N, P and K ($p < 0.05$). The AUEs of N, P and K were increased by 44.3–75.3%, 72.4–103% and 128–160%, respectively, by NPK + S, NPK + M and NPK + S + M compared with CK. In conclusion, the revival of planting LGM during the fallow period was considered an appropriate measure in the Loess Plateau and similar rain-fed regions due to its ability to improve the growth and nutrient utilization of subsequent winter wheat even in the short term, as well as the lack of negative effects exerted on other organic amendments in its effectiveness.

Keywords: legume green manure; winter wheat yield; water utilization; nutrient use efficiency; rain-fed region

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1. Introduction

Dryland farming practices face a major challenge in terms of efficiency and sustainability given the limited productivity of food crops. Dryland accounts for approximately

40% of the world's arable land, and approximately 51.2% of arable land is arid or semiarid and is mainly distributed in northwest and northern China [1,2]. Winter wheat (*Triticum aestivum* L.) is one of the major food crops planted in drylands worldwide and is also universally cultivated in northern China [3,4]. The Loess Plateau is a typical arid and semiarid area in northwest China, and the main crop planted is winter wheat. Infertile soil and water shortages are the main factors limiting agricultural development [1,2]. During the last two decades, winter wheat production has been extremely intensified and has relied more on chemical fertilizer than on organic fertilizer [5,6]. Chemical fertilizer has played a key role in enhancing crop productivity; however, its excessive application has become a dominant force behind many environmental threats [7–9]. The deficient application of organic fertilizer is not conducive to the further improvement in agricultural productivity and likely induces a decrease in soil organic carbon storage and degradation in the quality of soil [6,10,11].

Winter wheat is conventionally monocultivated from October to June, followed by a bare land fallow period from July to September, which is used to allow the soil to store water during the rainy summer [2]. However, poor and uneven precipitation still results in low and unstable wheat yields in dryland regions [6]. In addition, much evidence has indicated that the efficiency of bare fallow is low for retaining precipitation [12–14]. It implies that bare land fallow in the summer leisure period cannot sufficiently help to relieve the water stress of crop production in rain-fed regions. Conversely, a good alternative for water retention, mulching with plastic film, is extensively applied to ensure crop growth and has been confirmed to be effective in inducing excellent soil hydrothermal conditions and improving the utilization of water in deep soil [1,15,16]. Moreover, numerous studies suggest that bare land fallow not only results in a low utilization efficiency of natural resources but also likely leads to further soil degradation due to water or/and wind erosion [4,17]. Comprehensively, increasing the organic fertilizer input and the more efficient use of summer natural resources have become urgent issues that benefit to ensure food security and shrink the environmental footprint of agriculture in the Loess Plateau of China.

Increasing the organic input in the field can essentially improve the soil quality and supply available nutrients in the soil, thus promoting the absorption and utilization of a variety of soil-available nutrients as well as dry matter accumulation by crops [18,19]. Crop straw return to the field and the application of farmyard manure are both extensively adopted methods that have been demonstrated as viable in maintaining nutrients, soil structure and subsequent crop growth [5,6]. In addition, in traditional agriculture in China, legume green manure (LGM) is an important source of clean organic fertilizer that has been planted in the leisure period [3,19,20]. The application of LGM has been well shown to contribute to higher production of food and alleviate soil degradation without increasing chemical fertilizer applications, particularly in intensively and excessively cultivated systems [21,22]. Planting and incorporating LGM can provide N to soils through biological nitrogen (N) fixation and then increase the N supply to subsequent crops, which has attracted considerable research attention in agroecosystems worldwide [18–20,23,24]. Obviously, planting LGM can be a good alternative to make full use of the natural water and heat resources in the fallow period as well as to increase both organic and nutrient inputs for the subsequent crops.

However, although the application of LGM has been demonstrated to benefit the yield of subsequent crops as well as soil fertility and nutrient availability improvements in different regions [20–22,25], planting LGM during the fallow period only occurs in the small-scale rain-fed region in northern China. To promote the popularization of planting LGM, a more thorough understanding is needed, especially in semiarid and arid regions with extremely limited precipitation. The following questions must be addressed: (1) whether the planting of LGM during the fallow period will negatively affect the water utilization and yield of the subsequent crop when the viable water retention method is adopted; (2) whether the revived planting of LGM could alter the effectiveness of chemical fertilizers in the short term when chemical fertilizers are conventionally applied; and (3) how the planting of LGM would affect other organic amendments regarding the nutrient utilization of subsequent crops. As such, it is essential to investigate the effect of revived planting and incorporation of LGM on the productivity and water and nutrient use efficiencies of winter wheat, particularly when interacting with other organic amendments in the Loess Plateau of China.

Therefore, we conducted a field experiment for three consecutive years in a typical rain-fed agricultural area in the Loess Plateau of Shaanxi Province, China. On the basis of plastic film mulching and the conventional application of chemical fertilizers, in this experiment, we investigated how the revived planting of LGM combined with straw return and farmyard manure application affects the yield as well as the water and nutrient use efficiencies of winter wheat. It is essential to further optimize nutrient management and maintain agricultural production sustainability in dryland crop systems.

2. Materials and Methods

2.1. Site Description

This field experiment is located at the agroecological experimental station (35.12° N, 107.44° E) in Changwu County, Shaanxi Province. This region belongs to a typical rain-fed agricultural area in the southern Loess Plateau of China, with a semiarid continental monsoon climate. The annual mean temperature and precipitation for this area are 9.1 °C and 588 mm (1957–2012), respectively. The annual sunshine duration is 2230 h (1957–2009), and the annual frost-free period is 171 days. The agricultural production in this region entirely depends on natural precipitation. Approximately 50–60% of the annual rainfall occurs from June to September.

According to USDA soil taxonomy, the soil is classified as a Cumulic Haplustoll. It has a typical aridic and loamy texture, with medium fertility and high permeability. The topsoil (0–20 cm) in this area has a clay content of 24%, a silt content of 70% and a sand content of 6%. The pH is 8.1 with an electrical conductivity (EC) of 140 μs cm^{-1}. The contents of organic carbon, total N, total phosphorus (P), available N, available P and available potassium (K) are 8.32 g kg^{-1}, 0.95 g kg^{-1}, 0.66 g kg^{-1}, 13.7 mg kg^{-1}, 15.8 mg kg^{-1} and 150 mg kg^{-1}, respectively.

2.2. Experimental Design

A three-year field experiment was conducted from July 2016 to July 2019 including two main treatments and five sub-treatments which were arranged with a completely randomized split-plot design, as every five sub-treatments were randomly arranged in each main treatment plot. The two main treatments were (a) traditional wheat monoculture (G0) and (b) wheat planting after planting and incorporating LGM in the summer fallow period (G). The five sub-treatments were as follows: (a) no chemical application of N, P and K (CK), (b) applying chemicals N, P and K as basal fertilizers (NPK), (c) basal fertilization plus straw return (NPK + S), (d) basal fertilization plus farmyard manure application (NPK + M), and (e) basal fertilization plus straw return and farmyard manure application (NPK + S + M). There were 10 treatments in total examined in the experiment, in which each treatment plot 3 × 10 m^2 in size was repeated three times.

The basal fertilizer was applied with chemicals N, P and K at 135 kg N ha^{-1} (urea, 46% N), 52.4 kg P ha^{-1} (triple superphosphate [TSP], 13% P_2O_5) and 50 kg K ha^{-1} (potassium sulfate, 54% K_2O), respectively. Wheat straw (produced in a self-experimental field and collected from a nearby field) was applied at a rate of 9000 kg ha^{-1}. The local farmyard manure was applied at a rate of 30,000 kg ha^{-1}. The dry LGM contained 443.0 g kg^{-1} organic C, 30.0 g kg^{-1} total N, 4.0 g kg^{-1} total P and 26.4 g kg^{-1} total K (multi-year average values). The dry wheat straw contained 419.0 g kg^{-1} organic C, 3.58 g kg^{-1} total N, 1.0 g kg^{-1} total P and 13.0 g kg^{-1} total K. The dry farmyard manure contained 181.3 g kg^{-1} organic C, 8.7 g kg^{-1} total N, 5.5 g kg^{-1} total P and 4.3 g kg^{-1} total K.

2.3. Field Management

The flowchart illustrates the field experiment and management process, as shown in Figure 1.

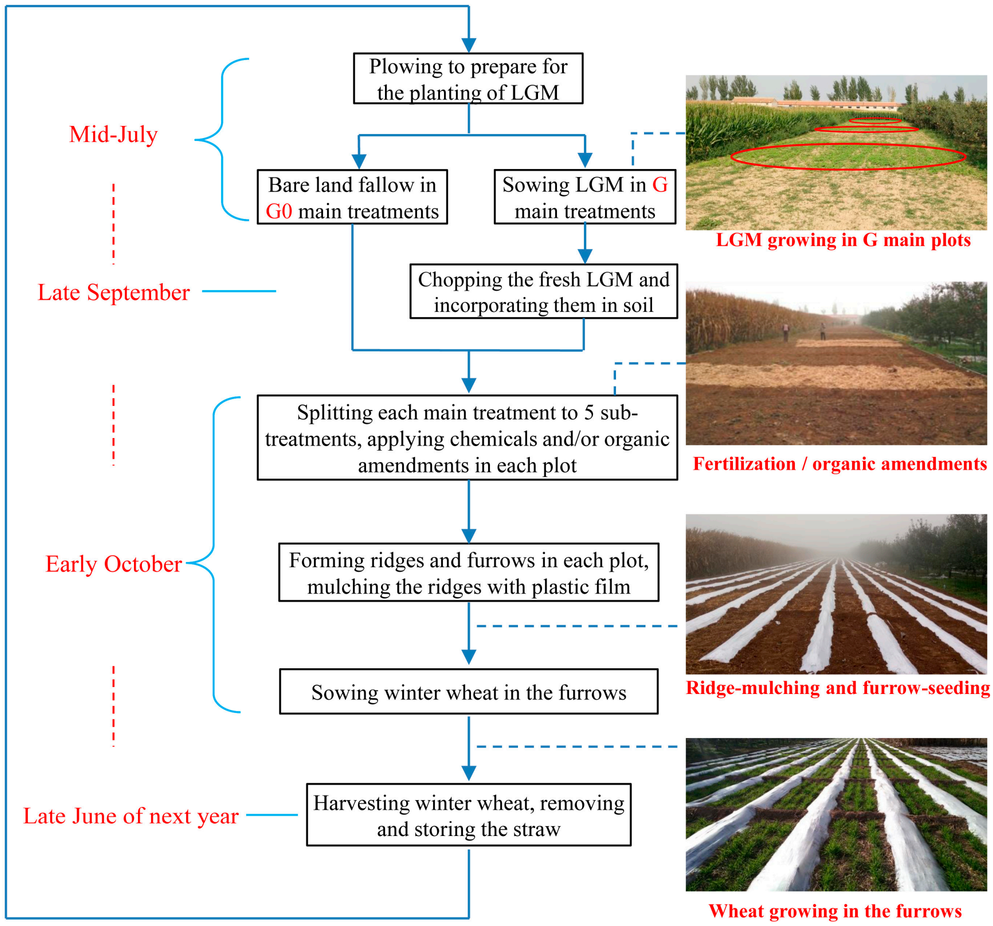

Figure 1. A flowchart illustrating the field experiment and management of a whole legume–wheat season. Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period.

In order to prepare for the planting of LGM, the entire trial field (all plots) was plowed to a depth of 10–15 cm with a rotavator in mid-July. Then, LGM (Huai bean, *Glycine ussuriensis* Regel et Maack.) seeds were evenly sowed at a rate of 90 kg ha^{-1} in the G plots in late July. The fresh LGM plant at full bloom stage was chopped into small pieces with a mowing machinery in late September. The small pieces were spread evenly in the fixed G plots and subsequently incorporated into soil using a rotavator in early October.

To prepare the seedbed of winter wheat prior to mid-October, chemicals N, P and K were applied to corresponding plots with NPK. Each S plot was evenly spread with hand-chopped wheat straw (in small pieces <5 cm). Local farmyard manure was applied in each M plot. After fertilization and organic amendments, all plots were immediately plowed (10–15 cm in depth) using a rotavator. Ridges and furrows were manually formed in each plot, which were both 55 cm in width. The ridges were used to be mulched with plastic film and the furrows were used to plant wheat. After all of these steps, winter wheat (Changhan 58, *T. aestivum* L.) was seeded in each furrow at a rate of 150 kg ha^{-1}. All treatments were uniformly adopted with ridge-mulching and furrow-seeding to retain soil moisture across the whole wheat growing seasons. The harvesting was conducted in late June of the next year. Nearly all wheat straw was removed from the trial field to prepare the straw return for the next wheat season.

2.4. Sampling and Measurement Methods

Soil samples were collected during the whole winter wheat growing season from 2016 to 2019, and multiple cores were selected for composite sampling in each plot. Soil samples for moisture determination were collected from 0 to 200 cm (every 20 cm layer) of soil depth every 15 days. The drying and weighing method was used to determine the soil water content. At the same time, the cutting ring method was used to collect each layer of undisturbed soil for the determination of soil bulk density (BD, g cm^{-3}).

Plant samples were collected every late June before the winter wheat harvest from each plot. In each plot, two separate small plots (squares) of 3.3-m^2 (3 × 1.1-m^2) in size were hand-sampled, in which one ridge and one furrow were contained. The grain and straw of wheat were hand-separated after oven-drying at 60 °C, and then were weighed to record the wheat yield (grain) and biomass (aboveground). Sub-samples of wheat grain and straw samples were both randomly selected and ground into powder for the determination of N, P and K concentrations in the wheat plant. The plant powder samples were digested using the H_2SO_4-H_2O_2 method. The N concentration in the digested solutions were determined with an automatic Kjeldahl analyzer (KjeltecT, Foss, Hillerød, Denmark), according to the Kjeldahl method [26]. After the molybdenum blue action, the P concentration in the digested solutions were determined with an ultraviolet spectrophotometer (UV-1900, Shimadzu, Kyoto, Japan), according to the molybdovanadate method [27]. The K concentrations in the digested solutions were determined using an atomic absorption spectrophotometer (Analyst 400, PerkinElmer, Shelton, CT, USA), according to the flame photometry method [28].

2.5. Data Calculation and Statistical Analyses

The soil water storage at the 0–200 cm depth was calculated as follows [1,12]:

$$SWS = \sum_{i=1}^{n} SM_i \times BD_i \times h_i \times 0.1 \quad (1)$$

where *SWS* is the total amount (mm) of soil water storage at the 0–200 cm depth at each sampling time; SM_i is the moisture content (%) in each layer i; BD_i is the soil density (g cm^{-3}) of each layer i; h_i is the soil depth (cm) of each layer i; and i (1–10) represents the soil layer number.

The total amount of water consumption and the associated water use efficiency of the wheat season were calculated as follows [1,14]:

$$WC = I + P + \Delta SWS - R - D \quad (2)$$

$$\Delta SWS = SWS_{Before} - SWS_{After} \quad (3)$$

$$WUE = \frac{Y}{WC} \quad (4)$$

where *WC* represents the total water consumption (mm) during each whole growth season; *I* and *P* represent the amounts from irrigation (mm) and precipitation (mm), respectively, during the whole wheat season; and *R* and *D* represent the rainfall losses (mm) through runoff and deep leaching, respectively. Because the experimental region is a typically arid and rain-fed agriculture region, the irrigation (*I*) was zero, and the runoff (*R*) and deep leaching (*D*) of rainfall were also negligible in our research. ΔSWS represents the soil water storage decrease during the whole season; SWS_{Before} and SWS_{After} represent the soil water storage at 0–200 cm depth before and after the whole wheat growth season, respectively; *WUE* represents the water use efficiency (kg ha^{-1} mm^{-1}).

The partial production of N, P and K fertilizers was calculated using the following equation [7]:

$$PFP = \frac{Y}{F_{N/P/K}} \quad (5)$$

where *PFP* represents the certain partial production (kg kg^{-1}) of N, P or K fertilizer; *Y* represents the grain yield of winter wheat in the fertilized treatment; and $F_{N/P/K}$ represents the input amount (kg ha^{-1}) of certain pure nutrients (N, P or K) from chemical fertilization.

The uptake and apparent use efficiency of fertilizer nutrients were calculated as follows [7,9]:

$$U = C \times Y \tag{6}$$

$$AUE = \frac{U_T - U_{CK}}{F} \times 100\% \tag{7}$$

where U represents the net nutrient uptake (kg ha^{-1}) of N, P or K; C represents the certain nutrient concentration in each part of wheat; Y represents the yield (kg ha^{-1}) of wheat grain or straw; AUE represents the certain apparent use efficiency of N, P or K fertilizers during the wheat season; U_T represents the total nutrient uptake (kg ha^{-1}) by wheat shoots in a certain treatment; U_{CK} represents total nutrient uptake (kg ha^{-1}) in the control treatment; and F represents the input amount of pure N, P or K from chemical fertilization.

The software of Statistical Package for the Social Sciences program (SPSS v19.0) was applied for statistical analyses. A split-plot design with two-way ANOVA was applied to check the differences in wheat yield and shoot biomass, as well as the inner nutrient concentrations and uptakes. Water consumption as well as water use efficiency and nutrient use efficiency were also analyzed using a split-plot design with two-way ANOVA. The significance was determined using the least significant difference test (LSD) at the 5% level.

3. Results

3.1. Wheat Production

As revealed by the short-term field experiment, the total precipitation was low during the initial two wheat seasons (242 mm in 2016–2017 and 192 mm in 2017–2018; Figure 2A,B). Frost occurred in early April 2018 and lasted for 2 days just at the winter wheat flowering stage (Figure 2C). The third wheat season (2018–2019) possessed the highest total precipitation (270 mm), and no extreme weather occurred. During the short term, winter wheat production was not regularly affected by agronomic measures containing planting LGM and fertilization regimes but was more affected by weather (Figures 2 and 3). Wheat grain yield and shoot biomass both decreased in 2018 compared with 2017. In the third trial year, the grain yield and shoot biomass were both the highest among the three wheat seasons from 2016 to 2019.

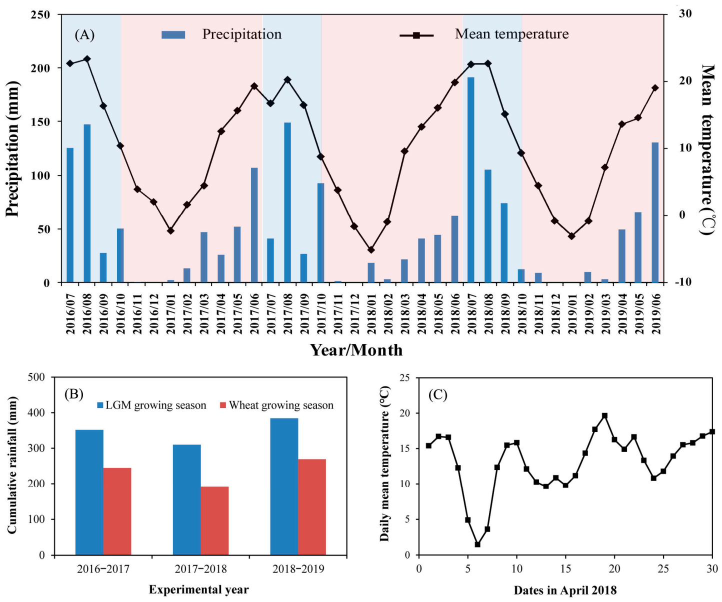

Figure 2. A description of precipitation and temperature from July 2016 to June 2019. Note: (**A**) shows the distribution of monthly cumulative precipitation and mean temperature, in which the blue and red shadows indicate the months in LGM growing and wheat growing seasons, respectively; (**B**) shows the cumulative rainfall in LGM and wheat growing seasons; (**C**) shows the daily mean temperature in April 2018 in which frost occurred.

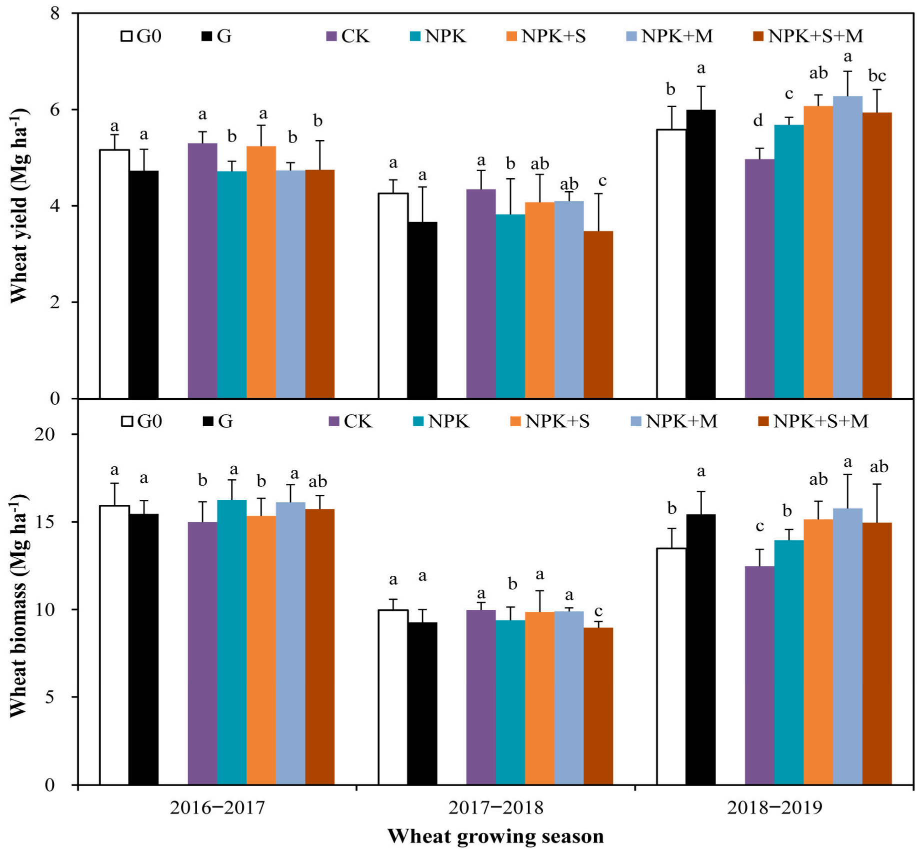

Figure 3. Effects of planting LGM and fertilization regimes on the yield and biomass of winter wheat during 2016-2019. Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; CK, no chemical application of N, P or K; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. A split-plot with two-way ANOVA was applied to check the differences in both wheat yield and biomass. Bars represent the mean values with their standard deviations (mean ± SD; n = 3). Different lowercase letters indicate significant differences among the two main treatments or among the five sub-treatments at a $p < 0.05$ significance level in a certain year.

Compared with the control (G0), planting and incorporating LGM (G) tended to reduce the yield and biomass of subsequent winter wheat in both the initial two wheat seasons, but not significantly (Figure 3; $p > 0.05$). Chemical fertilization (NPK) and its combinations with organic amendments (NPK + S, NPK + M and NPK + S + M) did not regularly affect the yield and biomass of winter wheat during the initial 2 years. In contrast, in the third year, G significantly increased the yield and biomass of winter wheat by 7.5% and 14.4%, respectively, relative to G0 ($p < 0.05$). In contrast, NPK increased the wheat yield and biomass by 14.3% and 11.9%, respectively, when compared with the control (CK). Furthermore, NPK + S, NPK + M and NPK + S + M significantly increased the wheat yield by 22.2%, 26.4% and 19.5%, respectively, and increased the wheat biomass by 21.4%, 26.3% and 19.8%, respectively, relative to CK ($p < 0.05$).

3.2. Water Utilization of Winter Wheat

Planting and incorporating LGM in the summer fallow period did not significantly affect the total water consumption (WC) of subsequent winter wheat in the whole growing season across the three trial years (Figure 4; $p < 0.05$). Fertilization regimes also did not regularly affect the WC of winter wheat in the initial two years. However, in the third year, NPK, NPK + S, NPK + M and NPK + S + M significantly increased the WC of winter wheat, which increased the WC by 5.2%, 6.4%, 9.2% and 9.5%, respectively, relative to CK ($p < 0.05$).

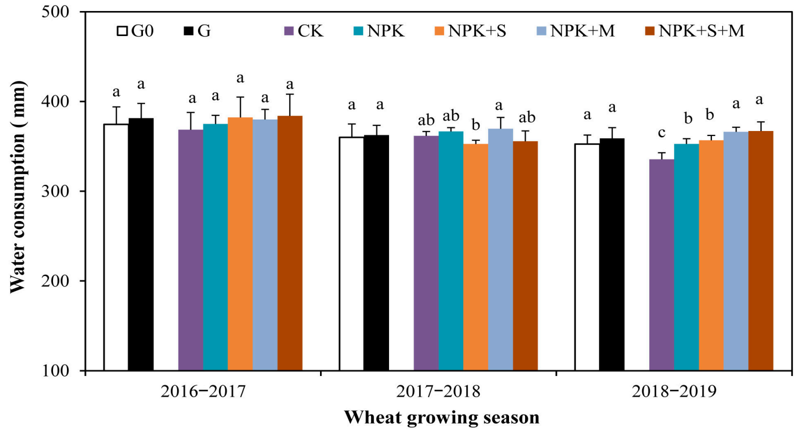

Figure 4. The total water consumption of winter wheat during each growing season from 2016 to 2019. Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; CK, no chemical application of N, P or K; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. A split-plot with two-way ANOVA was applied to check the difference in water consumption of winter wheat. Bars represent the mean values with their standard deviations (mean ± SD; n = 3). Different lowercase letters indicate significant differences among the two main treatments or among the five sub-treatments at a $p < 0.05$ significance level in a certain year.

Although the WC of winter wheat during the growing period was not greatly affected by the planting of LGM and fertilization regimes across the third season, the water use efficiency (WUE) of winter wheat was highly consistent with the wheat yield (Figures 3 and 4). Due to the low precipitation and the slight tendency to lower the wheat yield during the initial two wheat seasons, G significantly decreased the WUE of winter wheat when compared with G0. In contrast, G tended to increase the WUE of winter wheat relative to G0 during the third year, although the difference was not significant ($p > 0.05$). In contrast, fertilization regimes significantly affected the WUE of winter wheat in the third year, in which the NPK, NPK + S, NPK + M and NPK + S + M treatments increased the WUE by 9.2%, 15.2%, 16.3% and 9.1%, respectively, relative to CK (Figure 5; $p < 0.05$).

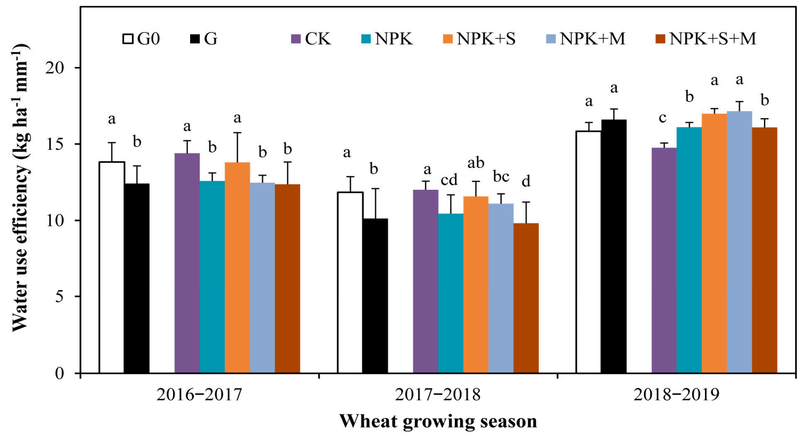

Figure 5. The water use efficiency of winter wheat during each growing season from 2016 to 2019. Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; CK, no chemical application of N, P or K; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. A split-plot with two-way ANOVA was applied to check the difference in the water use efficiency of winter wheat. Bars represent the mean values with their standard deviations (mean ± SD; n = 3). Different lowercase letters indicate significant differences among the two main treatments or among the five sub-treatments at a $p < 0.05$ significance level in a certain year.

3.3. Nutrient Utilization of Winter Wheat

Relative to G0, G exhibited a significant decrease in the partial factor productivities (PFPs) of N, P and K fertilizers during the initial two wheat seasons (Table 1; $p < 0.05$). However, fertilization regimes did not regularly affect the PFPs of chemical fertilizers during these two wheat seasons. In contrast, in the third year, G significantly increased the PFPs of chemical fertilizers by 7.7% relative to G0 ($p < 0.05$). In contrast, based on fertilization with chemicals N, P and K, organic amendments all had a tendency to increase the PFPs of chemical fertilizers during the third wheat season. The NPK + S, NPK + M and NPK + S + M treatments increased the PFPs of chemical fertilizers by 6.8%, 10.5% and 4.5%, respectively, relative to NPK ($p < 0.05$).

Table 1. Effects of planting LGM and fertilization regimes on partial factor productivity (PFP, kg kg^{-1}) of N, P and K fertilizers in winter wheat (2016–2019).

Factor/Level	2016–2017			2017–2018			2018–2019		
	PFP-N	**PFP-P**	**PFP-K**	**PFP-N**	**PFP-P**	**PFP-K**	**PFP-N**	**PFP-P**	**PFP-K**
Planting LGM									
G0	38.2a	98.4a	103a	31.9a	82.3a	86.3a	42.8b	110b	115b
G	33.8b	87.1b	97.3b	25.3b	65.3b	77.9b	46.0a	119a	125a
Fertilization regimes									
CK	--	--	--	--	--	--	--	--	--
NPK	34.9b	90.0b	94.4b	28.3b	72.9b	76.4b	42.1c	108.4c	114c
NPK + S	38.8a	100a	105a	30.2ab	77.8ab	81.5ab	45.0ab	116ab	121ab
NPK + M	35.1b	90.4b	94.7b	30.4a	78.2a	81.9a	46.5a	120a	126a
NPK + S + M	35.2b	90.6b	94.9b	25.7c	66.3c	69.5c	44.0bc	113bc	119bc
ANOVA *p* value									
G	0.013	0.013	0.013	0.003	0.003	0.003	<0.001	<0.001	<0.001
F	<0.001	<0.001	<0.001	0.001	0.001	0.001	0.006	0.006	0.006
G × F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.037	0.037	0.037

Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; CK, no chemical application of N, P or K; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. PFP-N, PFP-P and PFP-K represent the partial factor productivities of N, P and K fertilizers, respectively. A split-plot with two-way ANOVA was applied to check the differences in partial factor productivities of mineral fertilizers (N/P/K) of winter wheat. Data are mean values, and the following different lowercase letters indicate significant differences among the two main treatments or among the four sub-treatments in a certain year. A p value < 0.05 indicates a significant difference.

Obviously, the winter wheat only exhibited visible responses to LGM planting and fertilization regimes in the third trial year. In this year, G primarily affected the N concentration in winter wheat, which was increased by 4.6% and 12.2% in wheat grain and straw, respectively, relative to G0 (Table 2; $p < 0.05$). In contrast, fertilization regimes mainly affected the N concentration in both wheat grain and straw, as well as the K concentration in wheat straw (Table 2). The NPK, NPK + S, NPK + M and NPK + S + M treatments all significantly increased the N concentration in both the grain and straw of wheat ($p < 0.05$), although no significant difference existed among them. As the main K-storing organ, wheat straw increased in K concentration under NPK plus organic amendments during the third trial year ($p < 0.05$).

Specifically, planting and incorporating LGM significantly affected the N, P and K uptake in both the grain and straw of winter wheat during the third trial year (Table 3). Relative to G0, G increased the uptake of N, P and K by 18.8%, 11.7% and 18.8%, respectively, in winter wheat ($p < 0.05$). Moreover, NPK, NPK + S, NPK + M and NPK + S + M uniformly increased the uptake of N, P and K in both the grain and straw of winter wheat (Table 3). Based on NPK, various organic amendments further increased the N, P and K uptake in winter wheat, but no significant difference existed among them ($p < 0.05$).

Table 2. Effects of planting LGM and fertilization regimes on the concentrations (g kg^{-1}) of N, P and K in winter wheat (2018−2019).

Factor/Level	N Concentration		P Concentration		K Concentration	
	Grain	Straw	Grain	Straw	Grain	Straw
			Planting LGM			
G0	23.0b	6.43b	3.89a	0.88a	4.07a	14.6a
G	24.1a	7.22a	3.89a	0.92a	4.20a	14.7a
			Fertilization regimes			
CK	22.2b	5.65c	4.05a	0.93ab	4.05b	13.4c
NPK	23.5a	6.63b	3.87ab	0.85b	4.17a	13.5c
NPK + S	23.7a	7.00ab	3.83ab	0.89ab	4.15ab	15.2b
NPK + M	24.0a	7.49a	3.75b	0.87ab	4.14ab	15.1b
NPK + S + M	24.3a	7.36a	3.97ab	0.96a	4.17a	15.9a
			ANOVA *p* value			
G	0.032	0.028	NS	NS	NS	NS
F	0.004	<0.001	NS	NS	NS	<0.001
G × F	0.037	<0.001	NS	NS	0.048	<0.001

Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; CK, no chemical application of N, P or K; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. A split-plot with two-way ANOVA was applied to check the difference in N, P and K concentrations in wheat grain and straw. Data are mean values, and the following different lowercase letters indicate significant differences among the two main treatments or among the five sub-treatments in a certain year. A *p* value < 0.05 indicates a significant difference, and NS indicates a nonsignificant difference.

Table 3. Effects of planting LGM and fertilization regimes on the uptake (kg ha^{-1}) of N, P and K in winter wheat (2018–2019).

Factor/Level	N Uptake			P Uptake			K Uptake		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
				Planting LGM					
G0	129b	51b	180b	21.7b	6.94b	28.6b	22.7b	116b	138b
G	145a	69a	214a	23.3a	8.70a	32.0a	25.2a	139a	165a
				Fertilization regimes					
CK	110c	42c	153c	20.1c	6.98b	27.1c	20.1c	100b	120b
NPK	134b	55b	189b	21.9b	7.05b	28.7bc	23.7b	112b	135b
NPK + S	144a	64ab	208a	23.2ab	8.06ab	31.3ab	25.2a	138a	163a
NPK + M	151a	71a	222a	23.5a	8.30ab	31.8a	26.1a	144a	170a
NPK + S + M	145a	67a	213a	23.5a	8.71a	32.0a	24.7ab	143a	168a
				ANOVA *p* value					
G	0.017	0.007	<0.001	0.041	<0.001	0.008	0.005	0.002	0.002
F	<0.001	<0.001	<0.001	<0.001	NS	0.003	<0.001	<0.001	<0.001
G × F	NS	0.035	NS	NS	NS	NS	NS	NS	NS

Note: G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; CK, no chemical application of N, P or K; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. A split-plot with two-way ANOVA was applied to check the differences in uptakes of N, P and K in winter wheat. Data are mean values, and the following different lowercase letters indicate significant differences among the two main treatments or among the five sub-treatments in a certain year. A *p* value < 0.05 indicates a significant difference, and NS indicates a nonsignificant difference.

Planting LGM and organic amendments both increased the apparent use efficiencies (AUEs) of N, P and K during the third wheat season (Figure 6). Relative to G0, G significantly increased the AUEs of N, P and K by 88.0%, 102% and 93.2%, respectively ($p < 0.05$). In contrast, based on NPK, various organic amendments further increased the AUEs of N, P and K, and the net increase in the AUEs of N, P and K was 44.3–75.3%, 72.4–103% and 128–160%, respectively ($p < 0.05$). However, no significant interaction was observed between the planting of LGM and fertilization regimes in affecting the AUEs ($p > 0.05$).

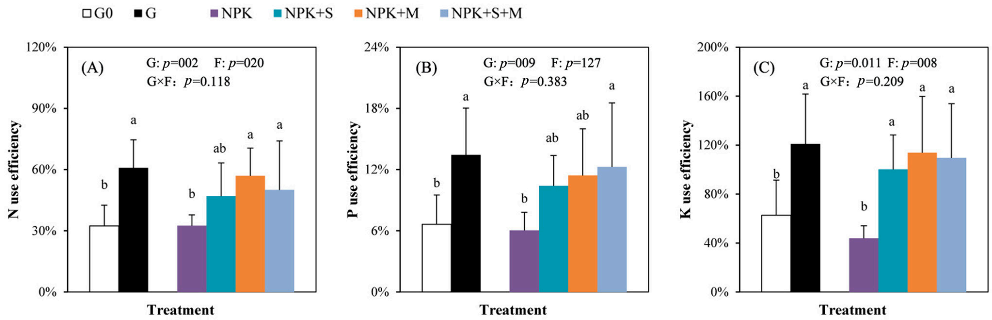

Figure 6. The apparent use efficiencies (AUE, %) of N, P and K fertilizers during the third wheat season (2018–2019). Note: (**A**–**C**) show the AUEs of N, P and K fertilizers, respectively. G0, traditional wheat monoculture without LGM application; G, wheat cultivation with planting and incorporation of LGM in the summer fallow period; NPK, basal fertilization with chemical N, P and K fertilizers; S, wheat straw return; M, farmyard manure application. A split-plot with two-way ANOVA was used to check the difference in the apparent use efficiencies of N, P and K in winter wheat. Bars represent mean values with their standard deviations (mean ± SD; n = 3). The different lowercase letters indicate significant differences among the two main treatments or among the four sub-treatments in a certain year at a $p < 0.05$ significance level.

4. Discussion

4.1. Wheat Yield Fluctuation

Planting and incorporating LGM in the summer fallow period tended to decrease the yield and biomass of subsequent winter wheat during the initial 2 trial years, though not significantly (Figure 3). Fertilization with chemicals N, P and K or chemical fertilization combined with organic amendments, including straw return and farmyard manure application, did not reliably increase either the yield or biomass of winter wheat during these 2 years (Figure 3). It implied that planting and incorporating LGM in the fallow period and the inclusion of organic amendments might not necessarily improve the growth of subsequent crops in the short term. This phenomenon may be due to the increase in soil water consumption caused by planting LGM during the fallow period, as well as the multiple negative effects of LGM residue on wheat germination, for instance, affecting the light, temperature and microenvironment and releasing allelochemicals from the roots in several species of LGM [14,28,29]. Moreover, organic amendments could also result in weed competition, temporal immobilization of soil nutrients by microorganisms and induced poor seedbed quality, as well as water and nutrient competition with succeeding crops [6,30,31]. As a result, both the planting of LGM and various organic amendments did not increase the yield of subsequent winter wheat (Figure 3). Otherwise, the initial 2 years were dry years with relatively low precipitation, and frost existed in early April 2018 and lasted for 2 days at the wheat flowering stage (Figure 2). It was speculated that the promoted growth of winter wheat by chemical fertilization and organic amendments could be more easily damaged by extreme weather, inducing a decrease in the yield and biomass of wheat specifically in the second year (Figure 3).

Theoretically, LGM can activate soil nutrients, fix atmospheric N and reduce N loss after being incorporated into soils [20,22]. Organic amendments, including crop straw return and farmyard manure application, can promote soil carbon sequestration and provide a variety of nutrients [19,32]; both amendments can improve the soil's physicochemical and biological properties and benefit crop production [1,8,32]. As evidenced, the planting of LGM and chemical fertilization combined with various organic amendments increased the yield of subsequent winter wheat in the third year, with general precipitation and no extreme weather, indicating their efficient improvement in winter wheat production in the short term (Figure 3).

4.2. Water Utilization of Wheat

Precipitation is usually the only source of water supporting crop growth in rain-fed agricultural regions; thus, the initial soil water storage and present rainfall are both essential for the growth of current crops. Although planting LGM was indicated to induce water competition with the subsequent crops, bare land fallow has been confirmed to cause a low efficiency in storing precipitation, a waste of natural resources and soil erosion [12,13]. Conversely, planting LGM has been indicated to have a considerable potential for alleviating the depletion of water storage in soil and maintaining the water balance in a similar agroecosystem [14]. In the current study, plastic film mulching was applied to winter wheat cultivation which can efficiently improve the harvest of rainfall and suppress ineffective evaporation [2,33,34]. Consequently, water consumption was not affected by planting LGM across the three trial wheat seasons (Figure 4); this proved that the water condition cannot be a limiting factor that works against winter wheat production in this system with the planting of LGM during the fallow period, consistent with previous studies from other regions [14,35].

The precipitation (less than 250 mm) in the initial two wheat seasons was much lower than the locally normal precipitation (approximately 300 mm) during the wheat growing season in this region. Fertilization could not enable plants to utilize more soil water and reliably increase the WC, especially in dry years (Figure 4). However, in the third wheat season (270 mm of rainfall), the planting of LGM, fertilization with chemicals N, P and K, and chemical fertilization combined with various organic amendments all promoted the growth of winter wheat, thus increasing the WC. The increased wheat yield certainly requires more canopy transpiration to promote the absorption of nutrients and dry matter production [1,36]. As a result, the wheat yield variation critically affected the WUE during the wheat season, in which the high yield of winter wheat generally corresponded to the high WUE (Figures 3 and 5); it also suggested that the planting of LGM and the inclusion of organic amendments were beneficial for improving the water utilization of subsequent winter wheat.

4.3. Nutrient Use Efficiency of Winter Wheat

The partial factor productivity of chemical fertilizers is closely related to the yield of crops. As planting LGM induced a slight tendency to reduce the subsequent wheat yield, the PFPs of fertilizers decreased in the initial two wheat seasons (Figure 3, Table 1). Various organic amendments did not stably affect the PFPs of chemical fertilizers in these 2 years. In contrast, related to the wheat yield increase, the PFPs of N, P and K fertilizers were increased by both planting LGM and implementing organic amendments in the third wheat season (Figure 3, Table 1).

Revived planting of LGM and chemical fertilization primarily increased the N concentration in both the grain and straw of winter wheat in the third trial year (Table 2). The appropriate enhancement of soil N supply can be achieved via chemical fertilization or LGM application, which is crucial for subsequent wheat nutrient accumulation and yielding [20,37,38]. Although organic amendments provided a certain amount of nutrients to the soil, they did not largely affect the nutrient concentrations in winter wheat due to the medium fertility in soil. In contrast, both planting LGM and fertilization did not largely affect the concentrations of P and K in winter wheat even in the third year, which was ascribed to the tested calcareous soil with low P availability and K-rich parent material (Table 2).

In the third year, planting LGM and various fertilization regimes efficiently increased the uptake of N, P and K in the wheat season. Planting LGM and implementing various organic amendments subsequently promoted the AUEs of chemicals N, P and K (Table 3, Figure 6). These results may be attributed to the improvement in wheat dry matter yield and soil biochemical and microbiological properties through the application of LGM and organic amendments [8,30,32]. However, planting LGM did not interact with other organic amendments in affecting the benefits of chemical fertilizers (Figure 6); the potential reason is that the relatively adequate nutrient inputs capped the further enhancement of crop nutrient uptake, which masked the interactive effect of various organic materials on the AUEs of nutrients [1,20]. Synthetically, this study confirmed the feasibility of revived planting of LGM in the fallow period, which can further improve the growth and fertilizer effectiveness of subsequent winter wheat even in the short term. Planting LGM cannot negatively affect the effectiveness of other organic amendments, such as straw return and farmyard manure application. Nevertheless, considering that fertilization and organic amendments affect nutrient bioavailability and that crop production is a time-dependent process, further research is required to accurately monitor the nutrient uptake and soil nutrient availability at different plant growth stages during a longer period. This knowledge will provide scientific implications and accurate evidence for nutrient management and productivity maintenance in dryland cropping systems.

5. Conclusions

In the current study, planting and incorporating LGM in the fallow period did not affect water utilization during the subsequent winter wheat season when plastic film mulching was adopted. In the third trial year, planting LGM efficiently increased the yield and biomass, as well as the WUE of the following wheat. Planting LGM primarily increased the N concentration in winter wheat but uniformly increased the uptake and use efficiencies of N, P and K fertilizers during the following wheat season. Based on the effectiveness of chemical N, P and K fertilizers, organic amendments, including straw return, farmyard manure application and straw return plus farmyard manure application, all increased the yield and WUE of wheat, further promoting the uptake and use efficiencies of N, P and K. Planting and incorporating LGM was beneficial to the growth and nutrient utilization of subsequent winter wheat even in the short term and did not negatively affect other organic amendments in regard to the effectiveness of fertilizers. Hence, planting LGM in the fallow period can be recommended as a reliable and sustainable practice for agricultural production in arid northern China.

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Abbreviations

LGM, legume green manure; G0, conventional winter wheat monoculture; G, planting and incorporating LGM followed by winter wheat planting; CK, no fertilization; NPK, basal fertilization with chemicals N, P and K; NPK + S, basal fertilization plus wheat straw return; NPK + M, basal fertilization plus farmyard manure application; NPK + S + M, basal fertilization plus wheat straw return plus farmyard manure application; WC, water consumption; WUE, water use efficiency; PFP, partial factor productivity; AUE, apparent use efficiency.

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