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Long-Term Optimization of Agronomic Practices Increases Water Storage Capacity and Available Water in Soil

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Abstract: In drylands, where the annual precipitation is low and erratic, improving the water storage capacity and the available water in the soil is crucial for crop production. To explore the effect of long-term agronomic management on water storage capacity and available water in the soil, four agronomic management systems were used (including the farmer's management model (FM), the high nitrogen input model (HN), the manure amendment model (MM), and the biochar amendment model (BM)) for eight consecutive years, and the variation in wheat yield and soil hydraulic, physical, and chemical properties in the 0–100 cm soil profile were investigated. The management practices varied in terms of seeding rates, nitrogen (N)-application strategies, and the application of manure or biochar. The results showed that, under the manure amendment model (MM), the wheat yield was increased by 17–35%, and the water-use efficiency was increased by 14–29% when compared to the farmer's management model (FM) and the high nitrogen input model (HN). However, no significant differences in wheat yield and water-use efficiency were found under the biochar amendment model (BM) compared to the HN. The high yield and water-use efficiency under the MM were mainly due to the higher saturated hydraulic conductivity, soil saturated water content, field capacity, and soil available water content, which led to an increase in the available water storage in the 0–100 cm soil profile by 29–48 mm. Furthermore, the MM also improved soil organic matter, porosity, root length density, and root weight density and reduced the soil bulk density, which are beneficial for the improvement of the above soil hydraulic properties. Therefore, it is a practical way to ensure high yield and high efficiency of crops in dryland by improving water storage capacity and the available water in the soil, which can be profoundly regulated by agronomic management.

Keywords: wheat yield; saturated hydraulic conductivity; field capacity; soil available water; soil organic carbon; manure

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1. Introduction

Soil plays a crucial role in storing and supplying water for crops. The total amount of soil water and its availability profoundly influence crop growth and grain yield, particularly in semi-arid and sub-humid regions, where crop growth is greatly restricted by insufficient precipitation. Soil water storage can be determined by the soil infiltration capacity (SIC) and the soil water-holding capacity (SWHC). Moreover, the portion of soil water accessible to crops is constrained by the permanent wilting point (PWP), as some water is tightly bound to soil particles and inaccessible to plants. A higher PWP reduces the amount of available water. Therefore, in areas with insufficient precipitation, enhancing the water storage capacity and the available water in the soil are crucial for sustainable crop production.

SIC, SWHC, and PWP are influenced by various physicochemical properties, such as organic matter content, bulk density, porosity, aggregate structure, texture, etc. Previous studies have demonstrated that increasing the soil organic matter content could enhance the rainwater infiltration rate and reduce evaporation, contributing to increased soil water storage [1,2]. Consequently, the long-term addition of exogenous organic matter significantly improved soil water-holding capacity [3]. A 1% increase in organic matter content has been reported to increase soil water storage by 2–5% [4]. Soil bulk density directly affects soil porosity, which determines the capacity of water infiltration and retention. Pores of different diameters play diverse roles in water movement and distribution. Macropores provide rapid drainage under the influence of gravity, and then, the water moves through micropores under the influence of capillary forces and is consumed by crop evapotranspiration. In addition, the redistribution of water is determined by mesopores [5]. Many studies have confirmed that increasing the proportion of soil mesopores and macropores can increase the amount of soil available water by decreasing the PWP [6,7]. Furthermore, soil porosity also affects crop root growth and the ability of water absorption of roots, which indirectly influences soil water availability. In addition to the above properties, a favorable soil aggregate structure can also improve soil pore space and aeration, which influences water retention and PWP [8]. In general, optimizing these hydraulic properties of soil is essential for improving water storage capacity and the available water in the soil.

Agronomic practices, such as seeding rates, nitrogen application strategy, and manure or biochar additives, have great effects on soil's physicochemical properties, which results in discrepant SIC, SWHC, and PWP [9–11]. Properly enhancing plant populations by increasing the seeding rate can enlarge root extension and distribution density in the soil profile, which are beneficial for increasing soil porosity. Additionally, stable structures can also be formed through the deposition of organic matter and microbial mucus after root decay, thereby improving the soil aggregate structure and pore distribution. Furthermore, soil bulk density could be decreased because a larger root system will return more organic matter back into the soil after harvest time [5,12,13].

Both above- and below-ground biomasses are significantly influenced by the application amount and timing of nitrogen fertilization. An appropriate N application rate guarantees the nutrient supply for crop growth. A split nitrogen application in the sowing and late growth stages not only increases the foraging behavior of roots, so that they penetrate farther into the deep soil layer for more nutrients in the early growth stages, but also enhances the N supply in the late growth stages. Thus, the above N application strategy could enlarge the distribution density of roots in the soil profile, which indirectly improves the soil structure by altering the soil pore size and distribution [14].

Adding organic amendments or fertilizers, such as composts, has been implemented for decades to maintain and enhance agricultural soil functioning. In addition to providing crop nutrients, organic fertilizer could quickly enhance a wide range of soil characteristics, including soil hydraulic properties [15]. It was reported that manure application could improve soil organic matter content and soil structure, which contributed to the reduction of bulk density and the increase in soil water infiltration and storage capacity [16,17]. Furthermore, manure also contains quantities of micronutrients that can be released slowly during the crop-growing season. Thus, the combined use of manure and inorganic fertilizers is advocated to promote crop growth by influencing plant population and root distribution.

As an emerging soil additive, biochar application has a positive effect on soil bulk density, porosity, aggregate structure, and water retention [10,18]. Chen et al. [19] found that biochar addition significantly improved soil aeration and permeability, leading to higher field capacity and available water content. Głąb et al. [20] indicated that, for every 1% increase in biochar addition, bulk density could be reduced by 3–5%, and the total soil porosity and available water capacity could be enhanced by 2% and 3%, respectively. Liang et al. [10] demonstrated that an appropriate amount of biochar application significantly improved soil hydraulic properties, including saturated water content and field capacity. In conclusion, numerous research has indicated that agronomic practices can effectively improve the hydraulic properties of surface soil. However, it is still unknown whether the hydraulic properties of subsoil can be improved by agronomic practices. In most dryland areas, the depth of the soil profile is generally deep, and the crop root can easily extend into the soil layer below one meter. Consequently, the water in the subsoil profile is also a crucial source of water during the crop-growing season. Therefore, investigating how long-term agronomic management affects the hydraulic properties of the 1 m soil profile is essential for understanding its impact on soil water storage capacity and availability.

Dryland agriculture accounts for approximately 75% of cropland in China [21]. In these areas, crop production mainly depends on natural precipitation, yet annual rainfall is low and unevenly distributed in different seasons. Thus, improving the collection, storage, retention, and utilization of precipitation is crucial for dryland agriculture. The Loess Plateau is a typical dryland in China, where wheat is the predominant crop, occupying 44% of the cultivated land. The region's annual precipitation ranges from 250 to 650 mm, with 60% of annual precipitation falling during the fallow period (July to September), whereas winter wheat grows from October through the following June. Thus, the water stored in the 1 m soil profile is a critical water source for wheat. However, the soil in this area is infertile, with low organic matter content, loose texture, poor capacity of water retention, and low available water content, which profoundly limits the storage of precipitation and its effective utilization by wheat [14]. In this study, we implemented four agronomic management systems for eight consecutive years on the Loess Plateau by changing the seeding rate, adjusting the N application strategy in rate and timing, and adding or non-adding manure or biochar. The winter wheat yield, water-use efficiency (WUE), soil hydraulic properties (including saturated hydraulic conductivity, soil saturated water content, field capacity, permanent wilting point, and available water storage), soil bulk density, soil porosity, and soil aggregate stability were measured. In doing so, we aimed to (1) verify whether the long-term application of agronomic practices can enhance water storage capacity and available water of soil and (2) understand the regulatory mechanism of agronomic management on soil available water capacity and crop drought resistance. The results of our study are expected to provide a theoretical basis for efficient water utilization and sustainable crop production for dryland agriculture. We hypothesized that (1) the optimization of agronomic practices could enhance water storage capacity and available water of soil and (2) the crop yield and water-use efficiency could be increased by improving the water storage capacity and the available water of soil in dryland.

2. Materials and Methods

2.1. Experimental Site Description

The experiment was conducted at Changwu Agro-ecological Experimental Station, Shanxi, China (35°12′ N, 107°44′ E, elevation 1220 m ASL, Figure A1 in Appendix A) from September 2014 to July 2022. The experimental station is located in the south–center of the Loess Plateau and is a typical dryland area. The average annual temperature is 9.13 °C, and the mean annual precipitation in the past 20 years (1994–2014) is 534 mm, with 40–70% occurring from July to September based on data collected from a meteorological station at Changwu [14]. The frost-free period is 171 days, and the buried depth of groundwater is 50–80 m. The soil is dark loessial soil (Calcic Kastanozems, FAO) with a silt loam texture. The soil of 0–100 cm layers was collected to determine the basic soil properties before planting in 2014. The basic soil properties are shown in Table 1.

Table 1. Basic chemical and physical properties of soil in 0–100 cm soil depth before sowing in 2014.

Soil Depth (cm)	pH	Bulk Density (g cm^{-3})	Soil Organic Carbon (g kg^{-1})	Total Nitrogen (g kg^{-1})	Available Phosphorus (mg kg^{-1})	Available Potassium (mg kg^{-1})
0–20	7.9 ± 0.2	1.30 ± 0.03	7.45 ± 0.78	0.86 ± 0.31	6.45 ± 0.38	127 ± 21
20–40	8.0 ± 0.1	1.43 ± 0.04	5.23 ± 0.84	0.6 ± 0.12	2.11 ± 0.21	101 ± 14
40–60	8.0 ± 0.1	1.44 ± 0.02	4.57 ± 0.48	0.51 ± 0.08	1.51 ± 0.19	94 ± 14
60–80	7.9 ± 0.3	1.41 ± 0.01	5.91 ± 0.24	0.61 ± 0.11	1.09 ± 0.09	78 ± 10
80–100	8.1 ± 0.2	1.37 ± 0.01	5.42 ± 0.35	0.67 ± 0.12	0.62 ± 0.04	60 ± 9

2.2. Experimental Design and Field Management

The field experiment consisted of four treatments, including the farmer's management model (FM), the high nitrogen input model (HN), the manure amendment model (MM), and the biochar amendment model (BM). For FM, the seeding rate was 120 kg·ha^{-1}, the N application rate was 120 kg·N·ha^{-1}, the phosphate (P_2O_5) application rate was 120 kg·P_2O_5·ha^{-1}, and all of the N and P_2O_5 fertilizers were applied as base fertilizer. In the HN, compared with the FM, the seeding rate was increased by 25%, and the N application rate was increased by 90 kg·ha^{-1}. All of it was used as topdressing during the jointing period. In the MM, compared with the HN, the N application rate was decreased by 60 kg·ha^{-1} (base fertilizer and top-dressed fertilizer both decreased by 30 kg·N·ha^{-1}), and 10,000 kg·ha^{-1} manure was also applied. In the BM, compared with the HN, the phosphate (P_2O_5) and top-dressed N application rate decreased by 30 kg·ha^{-1}, and 5000 kg·ha^{-1} biochar was applied. The experiment plots were 40 m^2 (10 m × 4 m) arranged as a randomized block design.

The N and P_2O_5 fertilizers used were urea (46.6% N) and calcium superphosphate (15.5% P_2O_5). The manure consisted of sheep dung and came from local farms. The biochar came from a charcoal factory in Changwu County, Shaanxi Province, and was black charcoal obtained by the carbonization (350–500 °C) of wheat straw residue, and the carbonization rate of the wheat straw was 31%. The properties of manure and biochar are shown in Table 2. Manure was applied before plowing every year, and the biochar was applied one time before plowing in 2014. Winter wheat (*Triticum aestivum* L., cv. Changhan 58) was sown in each plot with a row spacing of 20 cm by hand from 25 to 28 September in years from 2014 to 2021 and harvested from 29 June to 2 July of the following year. Winter wheat growth relies entirely on natural precipitation throughout its entire growth cycle, without any irrigation. Other agronomic practices in the experimental site are consistent with local conventional management practices.

Table 2. Basic chemical and physical properties of biochar and sheep dung in the experiment.

	pH	Total Nitrogen Content (g·kg^{-1})	Total Carbon Content (g·kg^{-1})	Total Phosphorus Content (g·kg^{-1})	Nitrate Nitrogen (mg kg^{-1})	Ammonium Nitrogen (mg kg^{-1})
Biochar	9.9	5.78	312	0.9	1.58	1.09
Manure	7.8	21.6	228	19.8	2.31	1.23

2.3. Sampling and Measurements

2.3.1. Yield and Water-Use Efficiency

The grain yield was sampled from three randomly selected 6 m^2 plots (6 m × 1 m) per treatment at harvest. The grain yield was measured after drying.

In 2022, post-harvest soil samples from 0–100 cm depth (in 20 cm increments) were taken using a 5 cm-diameter soil auger, repeated three times per plot, and mixed by layer. Soil water content (SWC) was determined by the oven-dry method. The following formulas were used to calculate the soil water storage (SWS) and water-use efficiency (WUE), according to Yang et al. [14].

$$\text{SWS (mm)} = \text{SWC}\cdot\text{BD}\cdot\text{D} \tag{1}$$

$$\text{ET (mm)} = \text{P} + \Delta\text{SWS} \tag{2}$$

$$\text{WUE } (\text{kg}\cdot\text{mm}^{-1}\cdot\text{ha}^{-1}) = \text{grain yield}/\text{ET} \tag{3}$$

where SWC is soil water content (*w*/*w*, %); BD is soil bulk density (g·cm^3); D is soil depth (mm); ET is evapotranspiration (mm); P is the effective rainfall during the growing season (mm); and ΔSWS is the change in soil water storage during the growing season (mm).

2.3.2. Soil Hydraulic Parameters and Physical Properties

Soil samples were collected at the harvesting stage in 2022 from a 100 cm deep stepped soil profile at three locations along a diagonal line. Sampling was conducted at 20 cm intervals, creating five layers: 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. Undisturbed soil cores were collected with 5 cm diameter and height cutting rings from the middle portion of each layer. Table 3 shows the soil characteristics of the test soil in our study.

Table 3. Soil characteristics of test soil.

Soil Characteristics	Abbreviation	Unit
Soil water content	SWC	*w*/*w*, %
Saturated hydraulic conductivity	Ks	mm·h^{-1}
Soil saturated water content	θs	*w*/*w*, %
Soil field capacity	FC	*w*/*w*, %
Permanent wilting point	PWP	*w*/*w*, %
Soil available water	PAW	*w*/*w*, %
Soil available water storage	PAWS	mm
Soil bulk density	BD	g·cm^3
Soil porosity	TP	%
Soil capillary porosity	CP	%
Mean weight diameter	MWD	mm
Geometric mean diameter	GMD	mm
Soil organic matter	SOC	g·kg^{-1}

Saturated hydraulic conductivity (Ks) was measured using the falling-head method [22]. Ks (mm·h^{-1}) was calculated using the following equation [23]:

$$\text{Ks} = \frac{\text{V}}{\text{St}}\cdot\frac{\text{L}}{\text{H}} \tag{4}$$

where t is the time elapsed (h), H is the constant water head height (cm), S is the cross-sectional area of the column (cm^2), L is the thickness of the soil (cm), and V is the volume of the leachate at time t (mL).

Each undisturbed soil within a cutting ring (the volume is 100 cm^3)was weighed to get the fresh weight (m_w), and then, the soils were immersed in water for 48 h until they were saturated and weighted (m_s) again to measure the soil saturated water content (θs) and soil porosity (TP). Then, the cutting ring with soaked soil was put on a flat bed of dry sand for 2 h to allow the excess water to drain out and be weighed (m_p) to measure the soil capillary porosity (CP). Then, leave the cutting ring with soil on the flat bed of dry sand for an additional 24 h and weigh (m_f) again to measure the soil field capacity (FC). Finally, the drained soil with the cutting ring was oven-dried to constant weight at 105 °C and weighed to get the dry weight (m_d) and the weight of the cutting ring (m_r). Then, the following formulas were used to calculate the BD, θs, TP, CP, FC, and FCS [24]:

$$\text{BD } (\text{g}\cdot\text{m}^{-3}) = (m_d - m_r)/\text{Vr} \tag{5}$$

$$\theta s\ (w/w, \%) = (m_s - m_d)/(m_d - m_r) \times 100\% \quad (6)$$

$$FC\ (w/w, \%) = (m_f - m_d)/(m_d - m_r) \times 100\% \quad (7)$$

$$TP\ (\%) = (m_s - m_d)/Vr \times 100\% \quad (8)$$

$$CP\ (\%) = (m_p - m_d)/r \times 100\% \quad (9)$$

$$FCS\ (mm) = FC \times BD \times D \quad (10)$$

where Vr is the volume of the cutting ring.

The permanent wilting point (PWP) was determined using the biological method according to Lucia H. Wiecheteck et al. [25]. The difference between field capacity (FC) and the permanent wilting point (PWP) is defined as the soil available water (PAW) [26]. The soil available water storage (PAWS) was calculated according to the following equations:

$$PAW\ (w/w, \%) = FC - PWP \quad (11)$$

$$PAWS\ (mm) = PAW \cdot BD \cdot D \quad (12)$$

2.3.3. Soil Organic Matter

The soil organic matter (SOC) was determined using potassium dichromate oxidation titration [27]. In 2022, post-harvest soil samples from 0–100 cm depths (in 20 cm increments) were taken using a 5 cm-diameter soil auger, repeated three times per plot, and mixed by layer.

2.3.4. Soil Aggregate Stability

The soil samples were collected at the harvesting stage in 2022 from a 100 cm deep stepped soil profile (20 cm intervals) at three locations along a diagonal line. The soil samples were collected from each layer and stored in aluminum boxes to ensure the original soil structure was preserved for water-stable aggregate analysis.

The soil aggregate stability was measured using the wet-sieving method [28]. The stability of soil aggregation was evaluated by mean weight diameter (MWD, mm), geometric mean diameter (GMD, mm), and the soil samples with a particle size of >0.25 mm (R0.25, %). The following formulas were used to calculate the MWD, GMD, and R0.25.

$$w_i = \frac{m_i}{m} \times 100\% \quad (13)$$

$$MWD = \sum_{i=1}^{n} {}_i w_i \quad (14)$$

$$GMD = e^{\left(\frac{\sum_{i=1}^{n} m_i \ln d_i}{\sum_{i=1}^{n} m_i}\right)} \quad (15)$$

$$R_{>0.25} = 1 - \frac{m_{<0.25}}{m} \quad (16)$$

In this equation, wi is the weight proportion of the grade i aggregate (%); mi is the weight of the different soil aggregates (g); m is the total weight of the soil aggregates (g); and di is the average diameter of the grade i aggregate (mm).

2.3.5. Root Length Density (RLD) and Root Weight Density (RWD)

The roots were sampled at the filling period in 2022. The root length density (RLD) and root weight density (RWD) were measured and calculated according to Yang et al. [14].

$$RLD\ (cm \cdot cm^{-3}) = Lr/Vr \quad (17)$$

$$RWD\ (g \cdot cm^{-3}) = Wr/Vr \quad (18)$$

where Lr is root length (cm), Wr is root weight (g), and Vr is the volume of the root auger core (cm^3).

2.4. Statistical Analysis

Statistical analyses were performed using the IBM SPSS Statistics 29 software package (IBM Company, Chicago, IL, USA). A one-way ANOVA assessed the effects of treatments on the soil properties, with significant differences evaluated by LSD at the 0.05 level. Pearson's correlation analysis (significance level of 0.05) was conducted to investigate the correlation among various soil hydrological properties and soil characteristics. The redundancy analysis (RDA) was performed by Origin 2024 (Origin Lab Corporation, Northampton, MA, USA) to identify the relationship between the response variables (soil hydrological properties) and the explanatory variables (soil characteristics).

3. Results

3.1. Winter Wheat Yield and Water-Use Efficiency of Long-Term Different Agronomic Practices

In this study, the average yields over the 8-year experimental period under FM, HN, MM, and BM were 4471, 5137, 6037, and 5493 kg ha^{-1}, respectively (Figure 1a). The average yields under MM and BM were significantly higher than FM, by 35.02% and 22.86%, respectively. Compared with HN, the yields of MM and BM were 17.51% and 6.93% higher, respectively. The average water-use efficiencies (WUE) over all eight years were 11.1, 12.5, 14.3, and 13.2 $kg \cdot mm^{-1} \cdot ha^{-1}$ under FM, HN, MM, and BM, respectively (Figure 1b). The WUE under HN, MM, and BM were 13.16%, 28.64%, and 19.34% higher, respectively, than that under FM. Compared with HN, the WUE of MM was 13.68% higher.

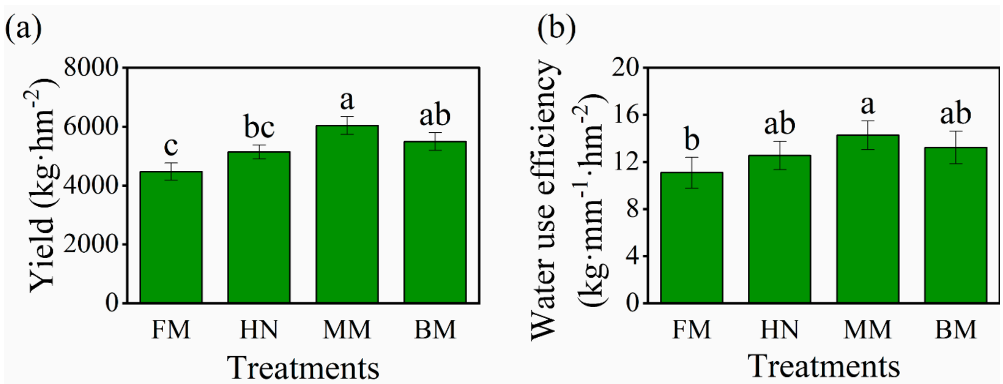

Figure 1. Average wheat yield (**a**) and water-use efficiency (**b**) over the 8-year experimental period (2014–2022) under different treatments. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

3.2. Soil Infiltration Capacity of Long-Term Different Agronomic Practices

As shown in Figure 2, the MM significantly improved the soil saturated hydraulic conductivity (Ks) in the 0–40 cm layers compared with the other treatments. Specifically, the MM significantly increased the Ks by 30.43–70.70% in the 0–20 cm soil layer and by 29.05–51.99% in the 20–40 cm soil layer, compared with the FM, HN, and BM. The BM significantly increased the Ks by 30.87% in the 0–20 cm soil layer compared with the FM.

3.3. Soil Water-Holding Capacity of Long-Term Different Agronomic Practices

The MM increased the soil saturation water content (θs) in all soil layers (Figure 3a). The θs under MM in the 0–20 cm and 20–40 cm soil layers were increased by 17.48–26.23% and 10.08–19.93%, respectively, compared with the FM, HN, and BM. The MM and BM could increase the soil field capacity (FC) in the 0–100 cm soil layer compared to the FM (Figure 3b). Compared with HN, they also increased the FC in the 0–40 cm soil layer. Specifically, the FC under MM was increased by 13.10–19.48%, 14.47–29.64%, 6.92–20.59%, 8.96–19.63%, and 10.68–16.25% in the 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm soil layer, compared with FM, HN, and BM, respectively. The permanent wilting point (PWP) of each soil layer is shown in Figure 3c. The BM increased the PWP in the 0–20 cm and 60–100 cm soil layers but decreased it in the 20–40 cm soil layer. The MM decreased PWP in the 40–60 cm soil layer but had no significant impact on other soil layers. The MM also increased the soil available water content (PAW) in each soil layer, similar to the θs (Figure 3d). The BM increased the PAW by 21.68% and 11.90% compared to the FM and HN in the 20–40 cm soil layer. In the 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers, the MM increased the PAW compared to the FM, HN, and BM by 18.62–22.08%, 11.48–35.65%, 12.53–37.91%, 8.77–20.25%, and 11.94–23.19%, respectively.

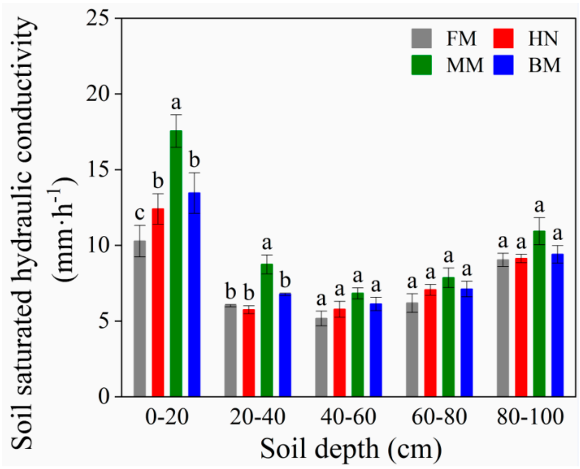

Figure 2. Soil saturated hydraulic conductivity under different treatments after 8 years of experimentation. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

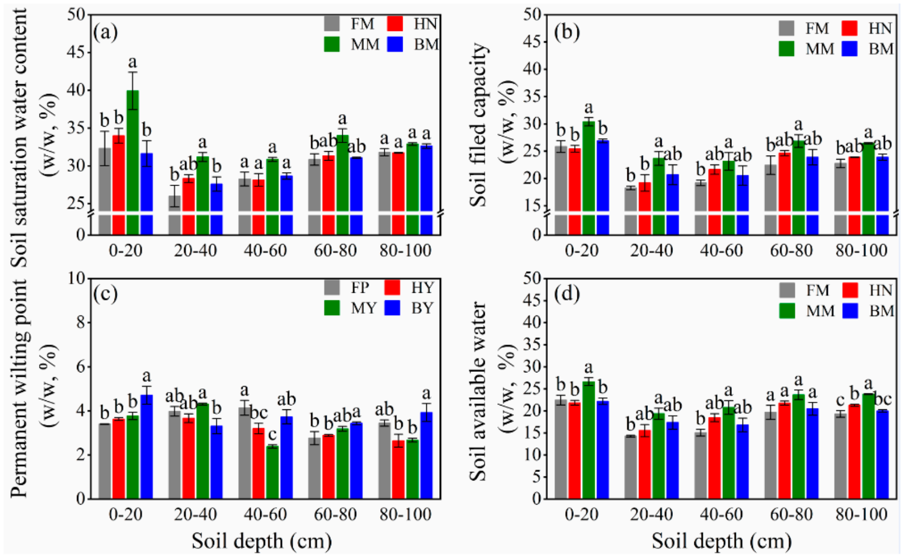

Figure 3. Soil saturation water content (**a**), soil field capacity (**b**), soil permanent wilting point (**c**), and soil available water content (**d**) under different treatments after 8 years of experimentation. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

3.4. Soil Water Effectiveness of Long-Term Different Agronomic Practices

As can be seen from Figure 4a, compared with the FM, the MM significantly reduced the unavailable water storage of the 40–60 cm and 80–100 cm soil layers and, thus, reduced the total unavailable water storage of the 0–100 cm soil layers by 7.61 mm. The MM increased the field capacity in the 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers by 3.41–7.08 mm, 6.11–9.86 mm, 2.14–8.30 mm, 3.54–8.94 mm, and 5.83–8.14 mm compared with the FM, HN and BM, respectively. As a result, the field capacity in the 0–100 cm soil profile was significantly increased by 27.85–40.15 mm. The MM significantly increased the soil available water content in the 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers by 4.85–7.49 mm, 3.70–10.13 mm, 4.88–14.10 mm, 3.02–8.16 mm, and 5.87–10.86 mm compared with the FM, HN and BM, respectively. Thus, the total soil available water storage in the 0–100 cm soil profile was significantly increased by 29.41–47.76 mm.

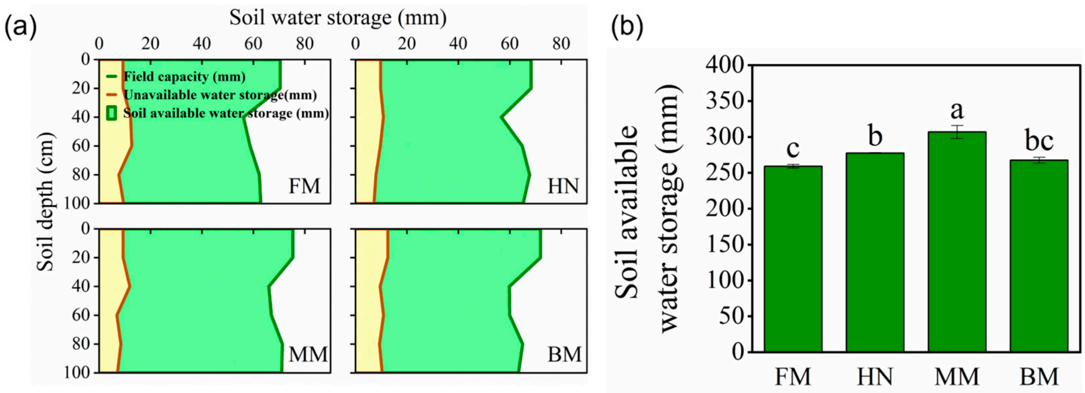

Figure 4. Soil water storage under different treatments after 8 years of experimentation. (**a**) Soil field capacity, soil unavailable water storage, and soil available water storage of different soil depths under different treatments; (**b**) total soil available water storage of 0–100 cm soil depth. FM—farmers' management model; HN—high nitrogen input model; MM: manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

3.5. Soil Organic Matter Content and Soil Bulk Density

Affected by different treatments and soil depths, the soil organic matter content (SOC) ranged from 8.36 to 22.22 $g \cdot kg^{-1}$ (Figure 5a). The results showed that the SOC content in the plow layer (0–20 cm) is higher than that in the deep layer (20–100 cm), and the SOC was higher in each layer of soil under the MM and BM. In the 0–20 cm soil layer, the SOCs of the MM and BM were 47.13% and 36.78% higher than the FM, and were 43.30% and 33.22% higher than the HN, respectively. In the 40–60 cm soil layer, the SOC in the BM significantly increased by 30.58% and 28.92% compared with the FM and HN, respectively. The soil bulk density (BD) in each layer is shown in Figure 5b. Both the MM and BM reduced the BD in each layer. In the 0–20 cm soil layer, the MM significantly reduced the BD compared to the FM, HN, and BM by 9.11%, 7.76%, and 7.36%, respectively. The BM reduced the BD by 1.89% compared to the FM. In the 20–40 cm soil layer, and compared with the FM and HN, the BD of the MM was significantly reduced by 9.52% and 5.91% respectively. And the BM was reduced by 5.77% and 2.01%, respectively.

3.6. Soil Porosity and Soil Capillary Porosity

As shown in Figure 6a, the different treatments affect each soil layer's soil porosity (TP). Under all treatments, the TP in the 0–20 cm soil layer was relatively high, with the lowest in the 20–40 cm soil layer. The MM increased the TP of each soil layer to varying degrees. In the 0–20 cm and 20–40 cm soil layers, the TP of the MM was significantly increased by 12.43% and 8.41% compared to FM, 8.16% and 3.58% compared to the HN, 16.85% and 8.58% compared to BM, respectively. However, the TP of the BM was 3.78%

and 7.44% lower than the FM and HN, respectively, in the 0–20 cm soil layer. The MM resulted in the highest soil capillary porosity (CP) in comparison to the FM, HN, and BM at the 0 to 80 cm depth. The CP in the 0–20 cm soil layer under the MM was significantly higher than under the FM and BM by 9.50% and 13.28%, respectively, and was higher than under the HN by 6.10%. However, the CP under the BM was lower than under the FM and HN by 3.33% and 16.34%, respectively (Figure 6b).

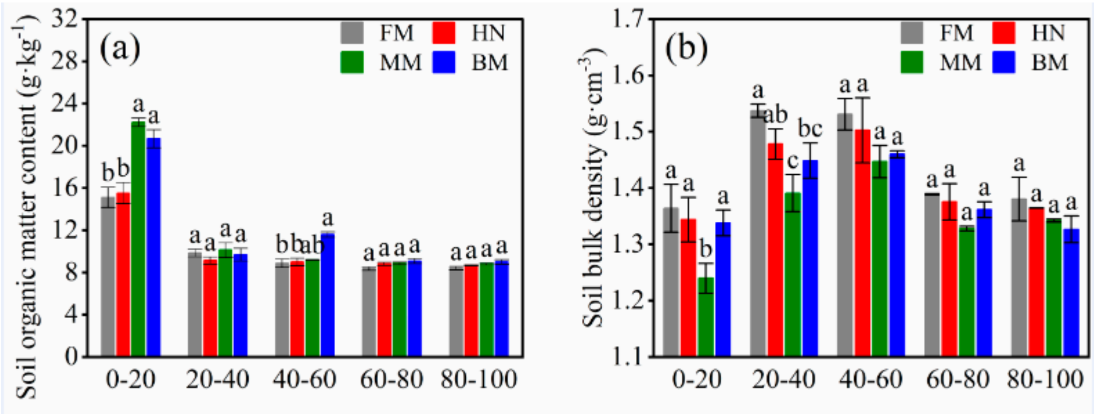

Figure 5. Soil organic matter content (**a**) and soil bulk density (**b**) under different treatments after 8 years of experimentation. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

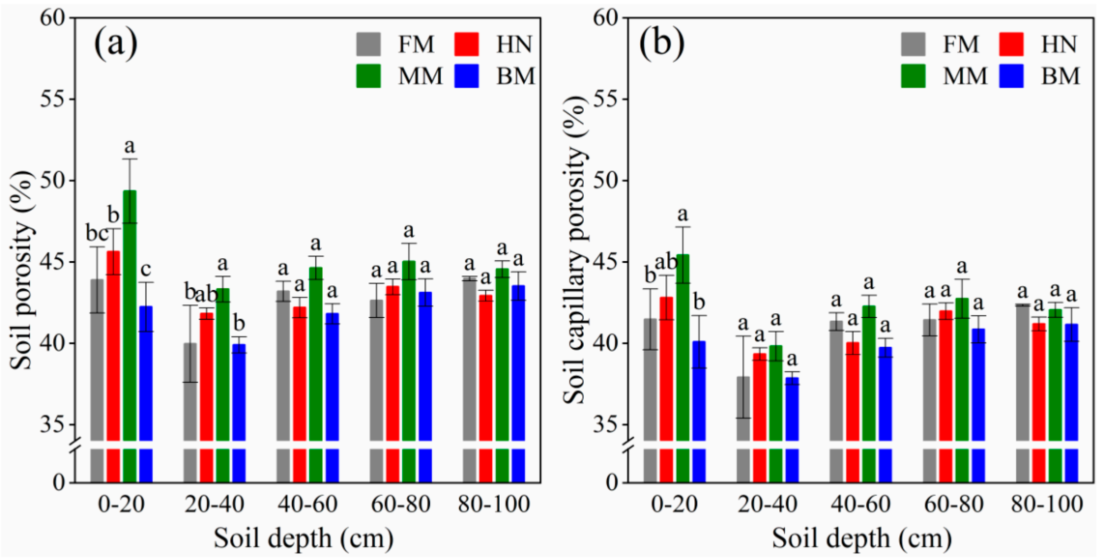

Figure 6. Soil porosity (**a**) and soil capillary porosity (**b**) under different treatments after 8 years of experimentation. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

3.7. Soil Water-Stable Aggregates' Stability

Table 4 shows the soil MWD, GMD, and R0.25 under different treatments. According to Table 4, different treatments have varying degrees of impact on the soil MWD, GMD, and R0.25 in the 0–100 cm soil layer. In the 0–60 cm soil layers, the MWD of each soil layer is lower than that in the 60–100 cm soil layers. The MM increased the soil MWD, GMD, and

R0.25 (excluding the soil layers of 40–60 cm and 80–100 cm) of each soil layer to varying degrees, but the BM reduced the MWD, GMD, and R0.25 in the 0–20 cm and 80–100 cm soil layers (Table 4). In the 0–20 cm soil layer, the MM increased the MWD, GMD, and R0.25 by 20.28%, 2.14%, and 8.96%, respectively, compared to the FM. In the 20–40 cm soil layer, the MM increased the MWD by 45.33–55.51%, the GMD by 8.06–9.52%, and the R0.25 by 40.76–56.05%, compared to the FM, HN, and BM. In the 60–80 cm soil layer, the MM increased the MWD and R0.25 by 17.93% and 21.44%, respectively, compared to the FM. In the 80–100 cm soil layer, the BM decreased the MWD and R0.25 by 16.12–25.31% and 21.15–24.16%, respectively, compared to the FM, HN, and BM.

Table 4. Soil aggregate stability under different treatments after 8 years of experimentation.

Soil Depth(cm)	Treatment	MWD (mm)	GMD (mm)	R0.25 (%)
0–20	FM	0.38 ± 0.014 c	0.72 ± 0.002 c	43.79 ± 0.74 c
	HN	0.55 ± 0.007 a	0.76 ± 0.004 a	51.84 ± 0.75 a
	MM	0.46 ± 0.007 b	0.74 ± 0.001 b	47.72 ± 0.56 b
	BM	0.35 ± 0.010 c	0.71 ± 0.002 d	41.25 ± 0.68 d
20–40	FM	0.32 ± 0.020 b	0.69 ± 0.006 b	35.32 ± 1.71 b
	HN	0.33 ± 0.003 b	0.70 ± 0.003 b	39.16 ± 1.43 b
	MM	0.50 ± 0.017 a	0.76 ± 0.005 a	55.12 ± 1.40 a
	BM	0.34 ± 0.012 b	0.70 ± 0.003 b	38.29 ± 0.63 b
40–60	FM	0.39 ± 0.011 a	0.72 ± 0.004 ab	46.13 ± 0.70 ab
	HN	0.40 ± 0.023 a	0.73 ± 0.007 a	50.78 ± 1.68 a
	MM	0.38 ± 0.030 a	0.72 ± 0.008 ab	46.68 ± 2.58 ab
	BM	0.38 ± 0.005 a	0.71 ± 0.002 b	44.24 ± 0.94 b
60–80	FM	0.45 ± 0.005 b	0.73 ± 0.001 a	48.24 ± 1.02 b
	HN	0.46 ± 0.039 ab	0.76 ± 0.027 a	50.15 ± 2.68 b
	MM	0.53 ± 0.008 a	0.76 ± 0.005 a	58.58 ± 2.10 a
	BM	0.43 ± 0.016 b	0.74 ± 0.004 a	50.66 ± 0.56 b
80–100	FM	0.49 ± 0.022 a	0.75 ± 0.004 a	55.75 ± 1.27 a
	HN	0.43 ± 0.012 a	0.74 ± 0.003 a	53.63 ± 0.48 a
	MM	0.47 ± 0.020 a	0.75 ± 0.002 a	55.65 ± 0.92 a
	BM	0.36 ± 0.014 b	0.70 ± 0.003 a	42.28 ± 0.83 b

Note FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean ± SE (n = 3). Different letters indicate a significant difference among the treatments at the same soil depth ($p < 0.05$).

3.8. Root Length Density and Root Weight Density

Figure 7 shows the root length density (RLD) and root weight density (RWD) under different treatments. In the 0–100 cm soil layer, the wheat roots under each treatment were mainly distributed in 0–20 cm, and the RLD and RWD gradually decreased with the deepening of the soil layer. The MM increased the RLD in all soil layers except the 40–60 cm soil layer compared to the FM and HN (Figure 7a). The MM had significantly higher RLD in the 60–80 cm and 80–100 cm soil layers than the FM, HN, and BM. The BM significantly improved the RLD in the 20–40 cm and 60–80 cm soil layers compared to the FM. The MM and BM increased the RWD in all soil layers compared to the FM and HN (Figure 7b). In the 0–20 cm soil layer, the MM increased the RWD by 16.34% compared to the HN. In the 60–80 cm soil layer, the MM and BM increased the RWD by 72.55% and 54.90% compared to the FM, and by 83.33% and 64.58% compared to the HN. In the 80–100 cm soil layer, the MM and BM increased the RWD by 78.57% and 25.00% compared to the FM and by 92.31% and 34.62% compared to the HN.

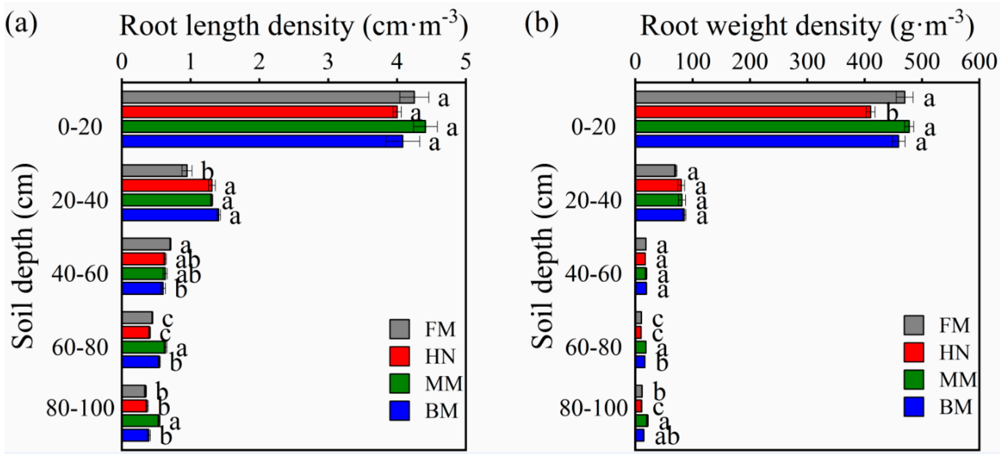

Figure 7. Root length density (**a**) and root weight density (**b**) at the filling period in 2022 under different treatments. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

3.9. Relationships between Soil Physicochemical Properties and Soil Hydrological Properties

A Pearson's correlation analysis revealed that the Ks was positively correlated with SOC, TP, CP, R0.25, MWD, GMD, RLD, and RWD and was negatively correlated with BD and clay (Figure 8). The θs, FC, PAW, and PAWS were positively correlated with SOC, TP, CP, R0.25, MWD, GMD, RLD, and RWD and were negatively correlated with BD but had not significantly correlated with sand, silt, and clay. The PWP was positively correlated with SOC, sand, RLD, and RWD and was negatively correlated with R0.25. The RDA further indicated that the soil physicochemical properties could account for 66.92%, with the first and second axes accounting for 64.12% and 2.80% of all variations, respectively (Figure 8).

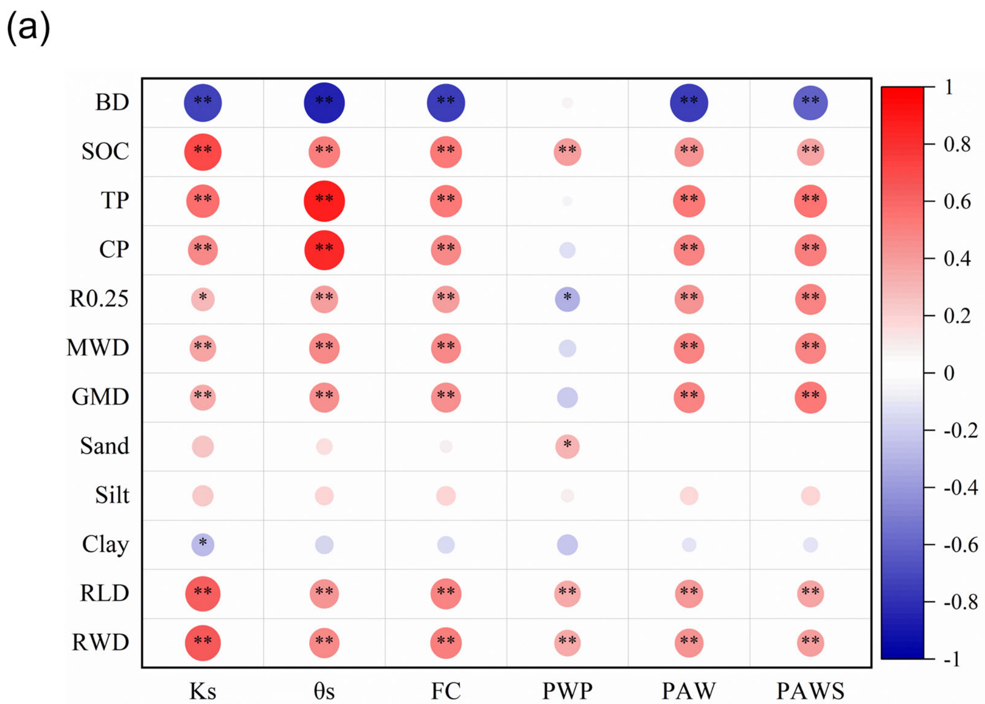

Figure 8. *Cont.*

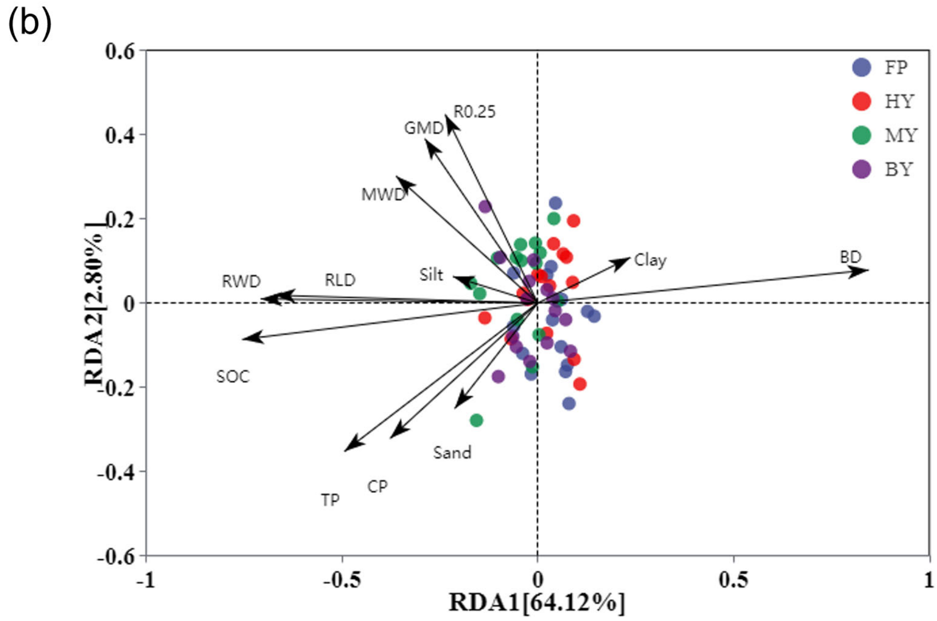

Figure 8. Pearson correlation (**a**) and redundancy analysis (**b**) were used to identify the relationships among the soil hydraulic properties and soil physicochemical properties under different treatments. The value of sand, silt, and clay content is shown in Table A1. The circles' color and size denote the relationship's direction and magnitude. * $p < 0.05$; ** $p < 0.01$.

4. Discussion

Our eight-year results indicated that the MM significantly increased both yield and WUE. The average yield of the MM was 6037 kg·ha^{-1}, which was 35.02% and 17.51% higher, respectively, compared to the FM and HN. Additionally, the average WUE under the MM was 14.3 kg·mm^{-1}·ha^{-1}, which was 28.64% and 13.68% greater than that under the FM and HN, respectively (Figure 1). Furthermore, we found that soil saturated hydraulic conductivity (Ks), soil saturated water content (θs), field capacity (FC), and soil available water (PAW) in the 0–20 cm and 20–40 cm soil layers were all improved under the MM. Consequently, the total available water storage in the 0–100 cm soil profile was greatly increased by 29.41–47.76 mm under the MM compared to the other treatments (Figures 2–4). In addition, our results also showed that the enhanced available water of soil under the MM was attributable to the significant improvements in the soil's physical and chemical properties. There was a higher soil organic matter, porosity, and aggregate stability and a lower soil bulk density in the 0–20 cm soil layer under the MM than those under other treatments. In conclusion, optimizing agronomic management in dryland farmland can effectively improve the water storage capacity and the available water in the soil, thereby ensuring a high yield and a high WUE of the crops.

Soil water storage is primarily influenced by soil infiltration capacity (quantified by saturated hydraulic conductivity), retention capacity (quantified by saturated water content and field capacity), and permanent wilting point. Increasing the saturated hydraulic conductivity (Ks) of the surface soil can strengthen the water storage capacity of the soil profile by allowing for more water to infiltrate into the subsoil [29]. In this study, it was observed that the Ks of the 0–20 cm and 20–40 cm soil layers were significantly increased under the MM (Figure 2). The Soil available water is calculated as the difference between the field capacity (FC) and the permanent wilting point (PWP) [26]. In the 0–20 cm and 20–40 cm soil layers, the MM had less effect on PWP, while it significantly increased FC. Thus, a higher soil available water (PAW) was observed under the MM (Figure 3). Higher root length density (RLD) and root weight density (RWD) were also observed under the MM (Figure 7). It was reported that a higher root density could significantly enhance soil porosity, thereby improving soil water infiltration and storage capacity [30,31]. Furthermore, a larger root system is able to capture more soil water, indicating that soil water availability could be increased simultaneously [14,29]. Thus, in dryland regions, it is a practical way to improve soil available water storage, which is resulted by higher soil saturated hydraulic conductivity, saturated water content and field capacity.

In this study, compared with the FM and HN, the MM significantly increased soil organic carbon (SOC) and total porosity (TP) in the 0–40 cm soil layer and reduced the BD (Figure 6). Previous studies have indicated that soil infiltration, soil water-holding capacity, and available water content can be improved by increasing the soil organic matter (SOM) and porosity or decreasing the soil bulk density (BD) [19,31]. Ju et al. [32] and Chen et al. [19] reported that both Ks and FC are positively correlated with soil organic carbon and pore characteristics. Our correlation analysis also confirmed that there were significantly positive correlations among Ks, θs, FC, PAW, PAWS, SOC, TP, CP, R0.25, MWD, and GMD ($p < 0.01$). Conversely, a significant negative correlation between the above indexes and the BD was also observed ($p < 0.01$) (Figure 8). Therefore, the Ks, θs, and FC in the 0–40 cm soil layer were increased under the MM due to the higher SOC and TP. In addition, a good soil aggregate structure not only increases the pore space and aeration of the soil but also improves water permeability and storage capacity, which is beneficial to the enhancement of soil water availability [8]. In this study, the MM greatly improved the soil aggregate structure, the content of water-stable macroaggregates, and aggregate stability when compared to the FM and HN (Table 4 and Figure A1). Furthermore, it also increased the root length density and root weight density (Figure 6). Thus, the MM treatment profoundly improved both the physical and chemical properties, which led to higher Ks, θs, FC, and PAW. However, under BM, a higher organic matter content was only observed in the 0–20 cm soil layer, and the soil's physical and chemical properties were less affected by BM, particularly in the subsoil. Consequently, only the saturated hydraulic conductivity of the surface soil was increased under BM.

The soil's physical and chemical properties are significantly influenced by agronomic practices. Properly increasing the sowing rate can increase both the above- and below-ground plant population, and a denser root system is able to improve soil porosity and soil aggregate structure [5,12]. The non-optimal N application strategy hinders the potential of crop growth. In general, the requirement for nutrients is relatively lower in early growth stages than during late stages. Therefore, splitting the application of N in different growth stages has positive effects on the development of the plant population [14]. Thus, both RLD and RWD were greatly increased under the MM compared to those under FM (Figure 7).

Numerous studies have shown that adding manure or biochar can increase the SOC and reduce the BD [10,19,33]. In this study, a higher SOC in the 0–20 cm soil layer was observed under the MM compared to the FM and HN (Figure 5). This finding was consistent with Tian et al. [34], which could be attributed to the higher carbon inputs from exogenous organic amendments and endogenous crop residues [35]. Moreover, the BDs in the 0–20 cm and 20–40 cm soil layers were decreased, and total porosity was increased under the MM (Figures 5 and 6). Manure is rich in organic matter, and the density of manure is lower than soil, which can loosen soil and reduce BD [36]. In addition, Bandyopadhyay et al. [37] found that applying organic fertilizers can significantly increase RLD and RWD. Thus, the larger root system under the MM is also beneficial to the improvement of BD and soil porosity (Figures 5–7). Aggregate stability in the 0–100 cm soil profile was also increased under the MM, which could be the result of the manure being rich in organic matter, polysaccharides, and humus, which cohere a lumpy soil structure by the functional groups' hydrogen bonding and Van der Waals forces [38]. It was reported that biochar contains an inert carbon structure that resists oxidative decomposition, which has strong resistance to chemical and biological degradation and can be converted into a stable carbon pool for long-term storage in the soil [39]. Thus, the BM significantly increased the SOC in the 0–20 cm soil layer in this study (Figure 5). However, the aggregate stability was less or even negatively affected by the BM (Table 3), unlike what has been observed in previous studies [19]. This may be due to the differences in biochar feedstock, pyrolysis conditions, application rates, soil and other environmental factors, or the fact that biochar had little long-term impact on soil microbial biomass and activities under field conditions [40,41]. Thus, although the study notes that biochar has several advantages, it also suggests that using it should be conducted with caution because of its potentially unfavorable long-term effects on soil aggregates.

5. Conclusions

This study demonstrated that sustainable high yields and WUE could be achieved in drylands by improving water storage capacity and the available water in the soil, which was profoundly affected by agronomic management. Our 8-year research showed that the MM significantly increased wheat yield and WUE compared to FM and HN. The increases in yield and WUE under the MM were due to its higher available water storage in the 0–100 cm soil profile. Furthermore, our results showed that the MM could enhance soil saturated hydraulic conductivity, soil saturated water content, field capacity, and soil available water in the 0–20 cm and 20–40 cm soil layers, all of which lead to a higher available water storage. In addition, under the MM, the soil organic matter, porosity, and aggregate stability were increased, and the soil bulk density was reduced in the 0–20 cm soil layer compared to those under other treatments. Root length density and root weight density were also increased under the MM, which is beneficial for the improvement of the soil saturated hydraulic conductivity and soil available water. In conclusion, favorable agronomic management in dryland farmland could effectively improve the water storage capacity and the available water in the soil, thereby ensuring high yield and high WUE of crops. However, the long-term sustainability of the benefits of this agronomic practice is uncertain and is also affected by other potential factors, such as soil quality. So, further research is needed to determine its long-term sustainability.

Author Contributions: Conceptualization, F.C. and S.W.; methodology, F.C. and W.Y.; software, F.C.; validation, F.C., W.Y. and S.W.; formal analysis, F.C.; investigation, F.C. and W.Y.; resources, S.W.; data curation, F.C.; writing—original draft preparation, F.C.; writing—review and editing, W.Y., S.W., L.Y. and X.D.; visualization, F.C.; supervision, S.W.; project administration, S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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

Appendix A

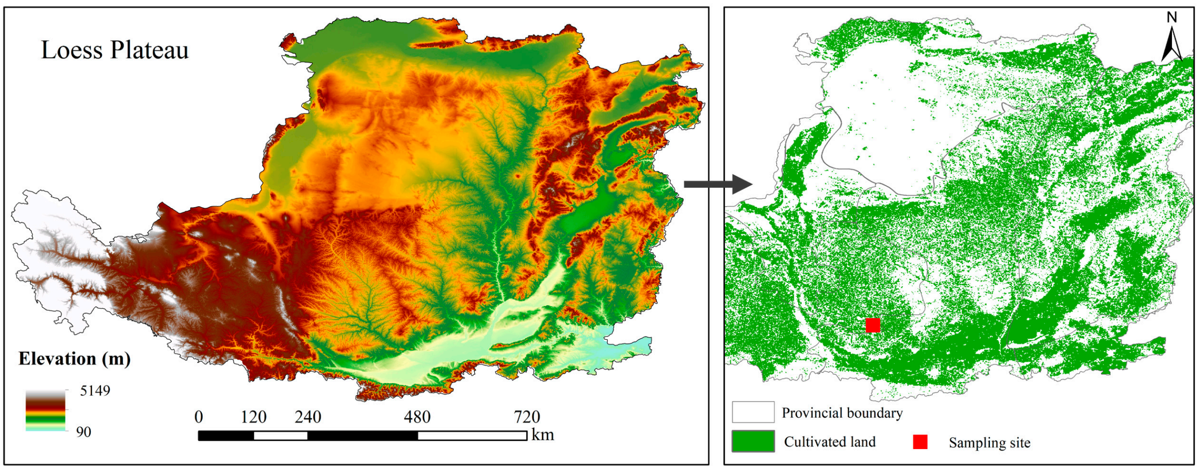

Figure A1. The map of the geographical location of the investigated area.

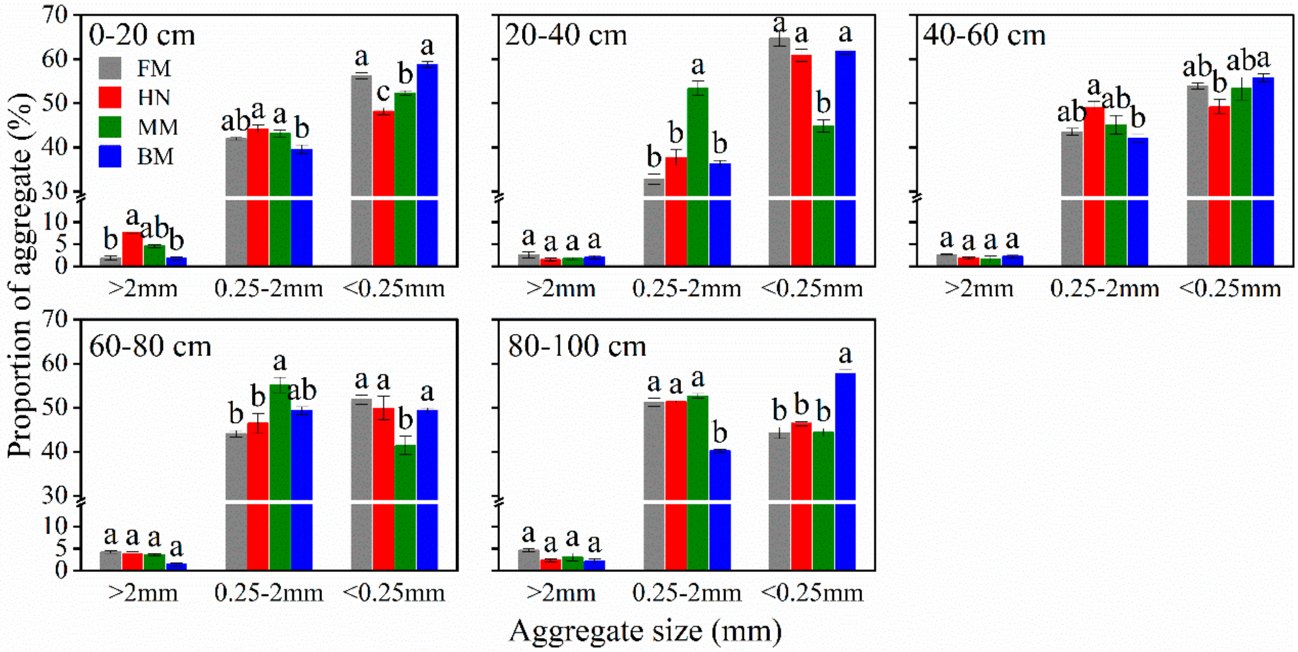

Figure A2. Soil aggregate size under different treatments. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean and standard error of the mean (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

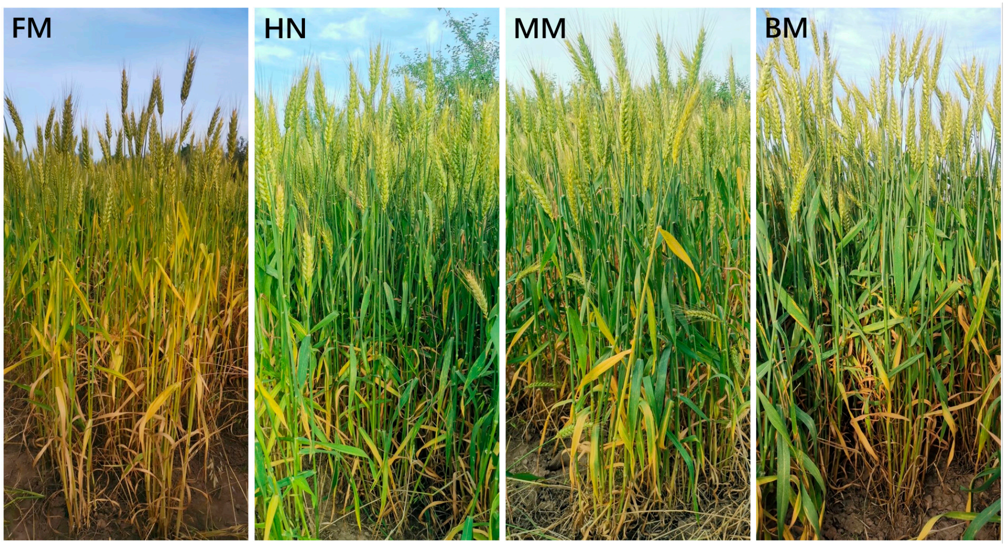

Figure A3. Winter wheat at filling period. FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model.

Figure A4. Collecting soil samples.

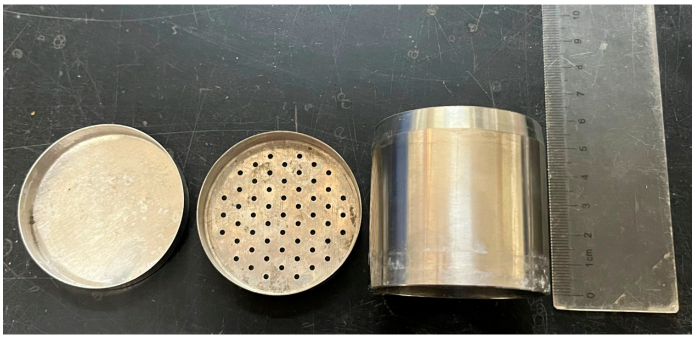

Figure A5. Cutting ring.

Table A1. Soil particle size composition under different treatments.

Soil Depth (cm)	Treatment	Sand (%)	Silt (%)	Clay (%)
0–20	FM	8.75 ± 0.60 b	63.67 ± 0.36 a	27.58 ± 0.64 a
	HN	8.79 ± 0.71 b	64.98 ± 0.97 a	26.24 ± 0.26 b
	MM	11.10 ± 0.20 a	63.71 ± 0.08 a	25.19 ± 0.25 b
	BM	8.96 ± 0.56 b	63.57 ± 0.28 a	27.47 ± 0.28 a
20–40	FM	9.67 ± 0.38 ab	63.54 ± 0.10 a	26.79 ± 0.28 b
	HN	8.39 ± 0.19 b	63.61 ± 0.20 a	28.00 ± 0.39 b
	MM	9.99 ± 0.77 a	64.16 ± 0.33 a	25.85 ± 1.10 b
	BM	6.44 ± 0.28 c	62.31 ± 1.37 a	31.25 ± 1.64 a
40–60	FM	8.75 ± 0.08 a	63.19 ± 0.49 a	28.06 ± 0.57 b
	HN	6.36 ± 0.20 a	62.99 ± 0.60 a	30.66 ± 0.41 b
	MM	9.13 ± 0.30 a	63.66 ± 0.24 a	27.22 ± 0.54 b
	BM	3.64 ± 0.25 b	56.05 ± 0.51 b	40.31 ± 0.72 a
60–80	FM	7.48 ± 0.27 a	60.69 ± 0.66 b	31.83 ± 0.40 b
	HN	5.00 ± 0.24 a	62.68 ± 0.23 a	32.33 ± 0.06 b
	MM	5.09 ± 0.17 ab	62.80 ± 0.25 a	32.10 ± 0.41 b
	BM	4.23 ± 0.12 b	58.52 ± 0.37 c	37.25 ± 0.49 a

Table A1. *Cont.*

Soil Depth (cm)	Treatment	Sand (%)	Silt (%)	Clay (%)
80–100	FM	5.34 ± 0.07 b	61.96 ± 0.11 a	32.70 ± 0.09 a
	HN	4.07 ± 0.22 b	62.97 ± 0.46 a	32.95 ± 0.25 ab
	MM	6.17 ± 0.05 a	61.91 ± 0.21 a	31.92 ± 0.25 b
	BM	4.61 ± 0.39 b	60.49 ± 0.56 b	34.90 ± 0.91 a

Note: FM—farmers' management model; HN—high nitrogen input model; MM—manure amendment model; BM—biochar amendment model. Data are shown as mean ± SE (n = 3). Different letters indicate a significant difference among the different treatments at the same soil depth ($p < 0.05$).

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