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Optimizing Soil Moisture Conservation and Temperature Regulation in Rainfed Jujube Orchards of China's Loess Hilly Areas Using Straw and Branch Mulching

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Abstract: The implementation of the "Returning Farmland to Forest" project in the loess hilly region of China has led to the establishment of large-scale economic forests, which have become the dominant industry driving local economic development. However, the region faces challenges such as drought, water shortages, and an uneven distribution of precipitation, which have a severe impact on the growth of economic forests, including jujube trees. Water stress significantly reduces yield and efficiency, posing a threat to the sustainable and healthy development of jujube ecological and economic forests. Therefore, this study aimed to address these issues by implementing straw mulching (SM) and jujube branch mulching (BM) measures in the mountainous jujube economic forests. Through long-term monitoring and statistical analysis, the study investigated the effects of different mulching treatments on soil moisture and soil temperature. The research findings reveal that both SM and BM significantly increased soil moisture in the 0–280 cm soil layer during the jujube growing season ($p < 0.05$). In both normal precipitation (2014) and drought (2015) years, SM increased average soil moisture content by 5.10% and 4.60%, respectively, compared to the uncovered treatment (CK). SM also had a positive impact on the soil moisture content in each layer of the soil profile. However, BM only increased soil moisture content in the 40–100 cm and 220–280 cm soil layers. Additionally, SM and BM reduced the variation of soil moisture, with SM showing a more significant effect in regulating soil moisture and achieving more stable moisture levels. During the jujube growing seasons in 2014 and 2015, SM and BM decreased soil temperature in the 0–10 cm soil layer. The temperature difference compared to CK decreased with increasing soil depth. SM had an overcooling effect, while BM reduced the temperature before the fruit expansion period and maintained warmth afterward. Both SM and BM also reduced the daily range and variation range of soil temperature, with SM having a more pronounced effect. The temperature of the 0–20 cm soil layer exhibited the strongest correlation with air temperature, and SM showed the weakest response. In conclusion, adopting straw mulching and jujube branch mulching in rain-fed jujube orchards in the loess hilly region not only saves materials and reduces costs but also contributes to water retention and temperature regulation. Straw mulching, in particular, plays a more significant role in moisture retention and temperature regulation and is advantageous for soil management in rain-fed jujube orchards. These research findings provide a scientific basis for optimizing water and heat management in orchards with limited water resources.

Keywords: soil moisture; soil temperature; straw mulching; branch mulching; jujube; loess hilly region

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1. Introduction

The jujube tree (*Ziziphus jujuba* Mill.) holds great economic importance in China's Loess hilly region [1]. Due to their remarkable adaptability to the delicate ecological conditions in the semi-arid Loess hilly region, jujube trees play a crucial role in mitigating soil and water loss and improving the overall ecological environment [2,3]. Jujube trees possess notable nutritional and medicinal value [4,5]. Since the implementation of cropland conversion to woodland in 1999, large-scale jujube orchards have rapidly emerged in the Loess hilly region [6]. By the end of 2015, over 500,000 hectares of jujube trees had been cultivated in northern Shaanxi, establishing jujube production as a vital pillar industry in the Loess Hilly Region [7,8]. Nevertheless, the arid environment of the Loess hilly region, characterized by limited precipitation, dry air, intense solar radiation, high evaporation rates, and rapid soil water depletion, is unfavorable for crop cultivation [9–11]. Reports indicate that soil drying has occurred in jujube orchards in the Loess hilly region, with drought and water scarcity emerging as the primary factors impeding the growth of jujube plants. In a study by Wang et al. [12] conducted in dense-dwarf jujube plantations in the Loess hilly region of China, it was observed that as the jujube trees matured, the moisture content in the root-zone soil decreased and the depth of the dry soil layer became slightly greater than the root depth. According to Zhang et al. [13], jujube trees were planted in soil that had dried out after four years of fallow periods. The soil water that was replenished in the 0–300 cm soil layer during the early stage was depleted by the fourth year, rendering the growth of jujube trees entirely reliant on the precipitation received in that particular year and its subsequent infiltration into the shallow soil layer. Evidently, the primary challenge confronting jujube production in the Loess hilly region is the scarcity of water resources, with soil moisture emerging as the principal impediment to the sustainable growth of jujube orchards in the area. It is crucial to address the significant challenge in the arid and water-scarce Loess hilly region, which involves implementing strategies to sustainably and judiciously utilize the limited precipitation resources, adopting soil management practices tailored to local conditions, enhancing the survival and preservation rate of jujube trees, improving the ecological environment, and fostering regional economic development.

Surface mulching is a primary technique employed to regulate soil moisture levels, enhancing soil permeability and water storage capacity [14,15]. Simultaneously, evaporation plays a significant role in the substantial reduction of soil moisture in dryland farming [16]. By employing materials such as plastic film, straw, sand, and gravel to create an isolation layer, the exchange of gaseous water between the soil and the atmosphere is obstructed. This technique reduces evaporation loss, enhances soil water retention, and promotes efficient water utilization [17–19]. Sun et al. investigated the impact of straw mulching on soil evaporation in a mature jujube orchard in the North China Plain [20]. They found that straw mulching significantly reduced the evapotranspiration rate in the experimental jujube orchard during both growing seasons. The investigation carried out by Wang et al. involved a soil box simulation experiment with a focus on jujube trees [21]. Their findings revealed that, when compared to alternative methods such as clean cultivation, strip white clover cover, and jujube branch mulch under the canopy in combination with strip white clover cover, the practice of using jujube branch mulch throughout the entire orchard resulted in the least amount of runoff and sediment yield. Simultaneously, it exhibited the highest infiltration rate. As such, the jujube branch mulch treatment was recognized as the most effective management approach for sloping jujube orchards in this study.

Soil surface mulching plays a crucial role in affecting solar radiation absorption, heat dissipation, and soil temperature regulation. The mulch acts as a barrier between the soil and air, decreasing the reflection of long-wave radiation from the soil surface and blocking direct solar radiation [22–24]. Surface mulching can effectively lower soil temperatures during periods of elevated air temperatures, thereby reducing the inefficient depletion of soil moisture [25]. In a monitoring study conducted by Suo et al., the impact of various surface mulching techniques, including grass cover, film mulching, straw mulching, and gravel mulching, on the ecosystem of apple orchards in the gully regions of the Loess

Plateau was examined [26]. The research findings demonstrated that straw mulching exhibited a superior effect in regulating soil temperature when compared to the other treatment methods. In a study conducted by Shu et al., the effects of various mulching methods on soil temperature in jujube orchards were investigated [27]. The research indicated that mulching with crushed jujube tree branches resulted in a considerable cooling effect as compared to conventional tillage practices.

In summary, while some researchers have made advancements in studying soil moisture and temperature changes with organic material mulch, such as straw and branches, in orchards, there remains a research gap concerning the specific application of organic material mulch in rain-fed sloping jujube orchards in the loess hilly areas. In the arid and water-deficient loess hilly areas, investigating the feasibility of utilizing organic material mulch in sloping jujube orchards to enhance water retention and regulate soil temperature holds significant scientific significance and offers promising prospects for the sustainable management of rain-fed jujube orchards in this region.

This study aims to investigate the effectiveness of implementing straw mulching and jujube branch mulching in rain-fed, sloping jujube orchards located in the Loess hilly region. By conducting long-term monitoring and employing mathematical statistics, the study aims to examine various aspects, including seasonal and vertical variation characteristics, profile variability, and soil moisture interactions across different soil layers under different mulching measures in different hydrological years. Furthermore, the study seeks to analyze the dynamic changes in soil temperature profiles, the daily range of soil temperature among different soil layers, the vertical variation characteristics of soil temperature, and their correlation with air temperature. The overall objective is to gain insight into the mechanisms responsible for water retention and temperature regulation under different mulching measures. Through comprehensive evaluation and analysis of the measures in terms of soil moisture and temperature changes and differences, the study intends to propose appropriate mulching techniques for rain-fed jujube orchards in the Loess hilly region. Ultimately, the aim is to promote the sustainable and healthy development of rain-fed jujube orchards in the area.

2. Materials and Methods

2.1. Overview of the Study Area

The study was conducted at the jujube water-saving base located in the Yuanzegou watershed, Dianzegou Town, Qingjian County, Yulin City, Shaanxi Province, China (Figure 1). This area is situated north of the Loess Plateau and is characterized by Loess hilly and gully topography. It experiences a semi-arid continental monsoon climate with extreme maximum and minimum air temperatures of 38.2 °C and −25.5 °C, respectively. The average annual air temperature is 8.5 °C, and the frost-free period spans 162 days. The average annual precipitation is 497 mm, with the months of June to September accounting for approximately 70% of the total. The research region predominantly consists of loess soil, which has good infiltration but low fertility. The fundamental physical characteristics of the 0–100 cm soil profile at the experimental site are presented in Table 1. The depth of the underground groundwater in the experimental area is estimated to be around 50 m, and the field capacity and wilting coefficient are approximately 25% and 7%, respectively (soil volumetric moisture content, the same below).

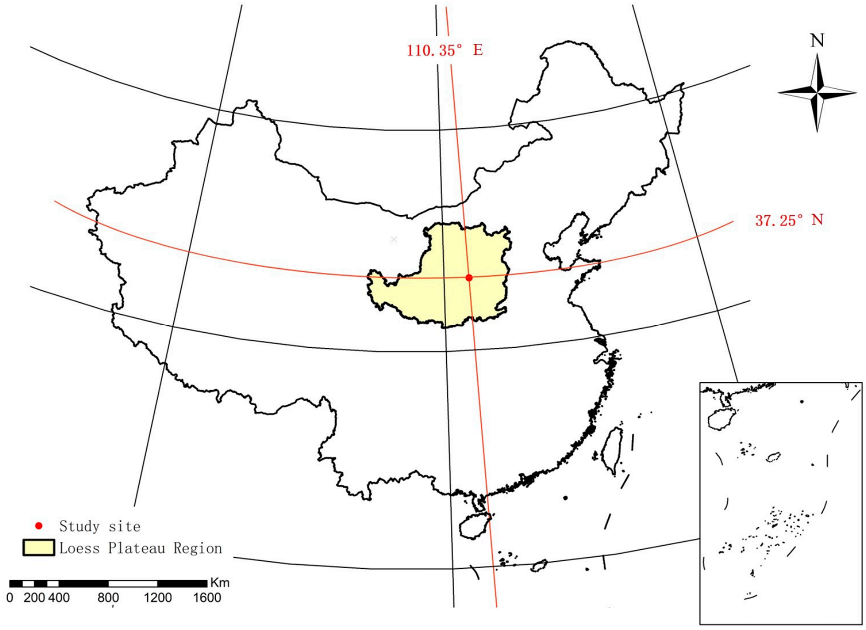

Figure 1. The geographical location of the study area.

Table 1. Soil properties of the 0–100 cm profile in the study area.

Soil Layer (cm)	Soil Bulk Density ($g \cdot cm^{-3}$)	Soil Particle Composition (%)			Saturated Moisture Content (%)	Field Capacity (%)	Saturated Hydraulic Conductivity ($mm \cdot min^{-1}$)
		Silt	Sand	Clay			
0–20	1.27	64.7	19.1	16.2	50.4	27.5	1.21
20–40	1.31	64.8	18.8	16.4	50.8	27.1	1.28
40–60	1.31	63.1	17.9	19	53.1	28.4	1.16
60–80	1.45	64.5	17.4	18.1	52.8	28.1	0.91
80–100	1.37	62.8	18.7	18.5	52.3	27.8	0.85

Note: clay (<0.002 mm), silt (0.002–0.02 mm), sand (0.02–2 mm). The saturated moisture content and field capacity are both expressed in terms of soil volumetric moisture content.

2.2. Experimental Design

A representative slope, typical of the research area, was selected as the experimental plot in the study. The plot was located on a 20° gradient slope. Jujube trees of the Lizao variety were planted in 2002, with a spacing of 2 m between plants and 3 m between rows. Dry farming techniques were employed to maintain soil moisture in the jujube orchard. Local management practices, including fertilizing and pruning, were followed.

The experimental treatments consisted of three conditions: absence of mulching (CK), straw mulching (SM), and jujube branch mulching (BM), as shown in Figure 2. Despite the piloting of straw mulching and branch mulching techniques in specific areas and orchards, their implementation in rain-fed, sloping jujube orchards located in Loess hilly regions was still in the early stages of development. Each treatment was applied twice. Maize straws and trimmed jujube branches were chopped to approximately 10 cm in length and used to cover the soil surface under the jujube trees. The mulch thickness aimed to reach 15 cm and was appropriately adjusted after the jujube growing phase to maintain the desired thickness.

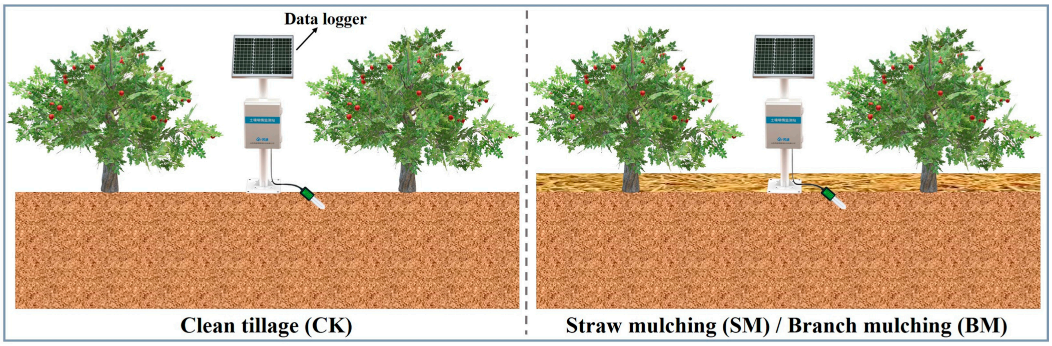

Figure 2. Diagrammatic representation of the placement of monitoring stations for soil moisture and temperature in the experimental rain-fed jujube orchard with no mulching (CK), straw mulching (SM), and jujube branch mulching (BM).

2.3. Experimental Index Measurement Method

2.3.1. Measurement of Soil Moisture and Temperature

In March 2014, an automated soil moisture and temperature monitoring system was installed in each experimental plot (Figure 2). Soil moisture content was measured using EC-5 soil moisture sensors manufactured by Decagon Devices Inc., located in Pullman, WA, USA. These sensors were buried at depths of 10, 20, 40, 60, 100, 160, 220, and 280 cm, respectively. To measure soil temperature, RR-7110 soil temperature sensors provided by Rainroot Scientific Ltd., Beijing, China, were employed. The sensors were buried at depths of 10, 20, 40, 60, and 100 cm. Before burying the sensors, the soil profile was excavated. After the sensors were planted at their designated depths, the soil was carefully backfilled to its original state. The automated monitoring system collected and recorded data at intervals of 2 min and 10 min, respectively.

2.3.2. Meteorological Data

To collect long-term meteorological data including wind speed, wind direction, solar radiation, air temperature, relative humidity, and precipitation, a small automatic weather station (AR5 automatic weather station; Avalon Scientific, Inc., Jersey City, NJ, USA) was installed in an open space within the research area. The weather station recorded data at 10-min intervals. Additionally, data was averaged and archived every 30 min to provide a comprehensive overview of the meteorological conditions.

2.4. Data Analysis

2.4.1. Analysis of Soil Moisture and Temperature Variability

The variation in soil moisture and temperature under different mulching treatments was assessed using two metrics: the coefficient of variation (C_v) and the extreme value ratio (K_a). C_v, as defined by Shechtman [28], is the ratio of standard deviation (σ) to the mean (μ):

$$C_v = \frac{\sigma}{\mu} \tag{1}$$

The C_v provides an indication of the variability of soil moisture and temperature. As C_v increases, the variability increases, indicating greater fluctuations in soil moisture and temperature.

The K_a (extreme value ratio) is calculated using the following formula, as described by Wei et al. [29]:

$$K_a = \frac{x_{max}}{x_{min}} \tag{2}$$

where x_{max} represents the highest soil temperature recorded and x_{min} represents the lowest soil temperature recorded. The K_a measure helps evaluate the magnitude of temperature fluctuations in the soil. A higher K_a value suggests more pronounced temperature changes, while a lower K_a value indicates more stable and gradual temperature variations.

2.4.2. Grey Relational Analysis of Soil Moisture in Different Soil Layers

Grey relational analysis is a method that assesses the relationship between a research object and its influencing factors by comparing their curves' distance. This analysis can establish a quantitative scale for the degree of soil moisture change and examine the numerical connection between soil moisture changes in different soil layers [30]. Wang et al. [31] provided the following calculation procedures:

1. Establish the reference sequence $x_0(k)$ and the comparison sequence $x_i(k)$:

$$x_0 = (x_0(1), x_0(2), \ldots, x_0(k)) \quad (3)$$

$$x_i = (x_i(1), x_i(2), \ldots, x_i(k)) \; i = 1, 2, \ldots, q \quad (4)$$

2. Normalize the data using the mean value approach to ensure consistency:

$$x_i(k) = \frac{x_i(k)}{\frac{1}{m}\sum_{k=1}^{m} x_i(k)} \quad (5)$$

The normalized sequence is represented as x_i*:

$$x_i{}^* = \left(x_i(1)^*, x_i(2)^*, \cdots, x_i(k)^*\right) \quad (6)$$

3. Calculate the gray relational coefficient $\xi_i(k)$ between $x_0(k)$ and $x_i(k)$:

$$\xi_i(k) = \frac{min_i min_k|x_0(k) - x_i(k)| + \rho max_i max_k|x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho max_i max_k|x_0(k) - x_i(k)|} \quad (7)$$

where ρ is the resolution coefficient, typically in the range [0, 1], commonly set to 0.5. A lower value indicates higher resolution. $|x_0(k) - x_i(k)|$ represents the absolute difference between x_0 and x_i at the k-th index. $min_i min_k|x_0(k) - x_i(k)|$ and $max_i max_k|x_0(k) - x_i(k)|$ are, respectively, the two-level minimum difference and the two-level maximum difference.

4. When conducting gray relational analysis over a long-time scale, numerous relational coefficients are obtained, providing the degree of connection between the comparison and reference sequences at various time nodes. However, analyzing all of these coefficients collectively would result in duplicate labor, so integration is required. The final gray relational grade (ξ_i) in this study is calculated as the average value of the relational coefficients across all time nodes:

$$\xi_i = \frac{1}{q}\sum_{i=1}^{q} \xi_i(k) \quad (8)$$

The closer the gray relational grade is to 1, the greater the correlation between the factors.

A one-way analysis of variance (ANOVA) with Tukey's post-hoc test was conducted to separate the means at a significance level of $p < 0.05$.

3. Results

3.1. Effects of Different Mulching Measures on Soil Moisture

3.1.1. Seasonal Variations in Soil Moisture Content under Different Mulching Measures

Regardless of the mulching measures employed, the seasonal variation in soil moisture content appeared to follow a similar trend across different precipitation years (Figure 3A,B). Under the influence of precipitation, evaporation, and other variables, the soil moisture content exhibited a curved pattern of change. When rainfall occurred, the soil moisture content increased rapidly; however, once the rainfall ceased, evaporation became dominant, leading to a rapid decline in soil moisture.

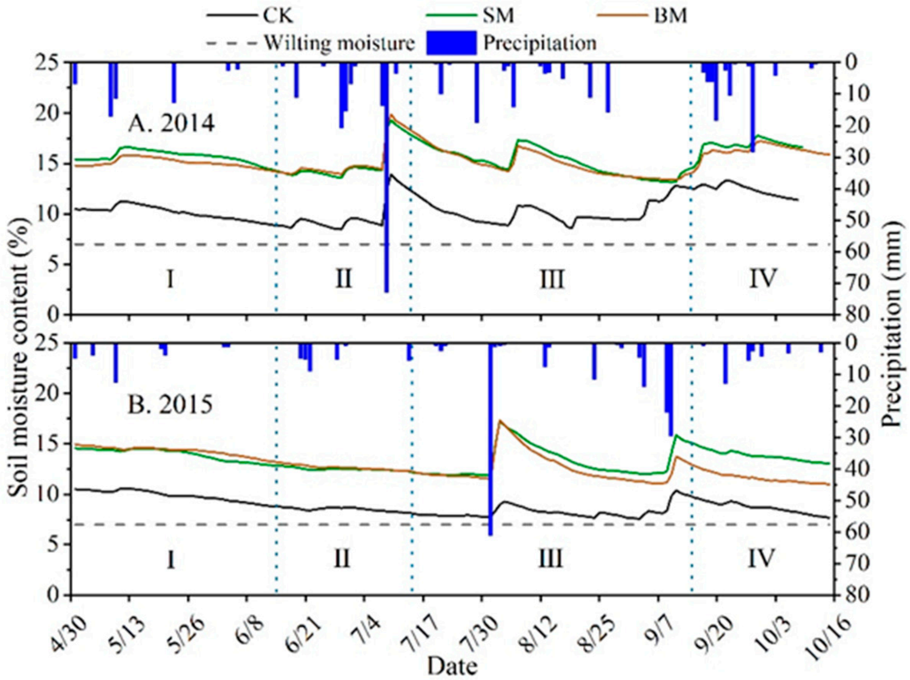

Figure 3. Changes in the daily average soil moisture in the 0–280 cm soil layer of the experimental rain-fed jujube orchard under three different mulching measures (CK, SM, and BM) over the 2014 (**A**) and 2015 (**B**) growth seasons. (I) Sprouting and leaf spreading period, (II) Flowering and fruiting period, (III) Fruit expansion period, and (IV) Fruit ripening period.

The soil moisture content under the three mulching measures exhibited distinct patterns during different stages of the jujube trees' growth in the 2014 season (Figure 3A). During the sprouting and leaf spreading periods, the soil moisture content decreased due to limited effective rainfall (only 48.2 mm) and increased evaporation caused by rapidly climbing air temperatures. The jujube orchard's evapotranspiration water consumption exceeded the precipitation supplement, depleting soil water reserves and leading to a continuous decrease in soil moisture. Subsequently, during the flowering and fruiting periods, the soil moisture content experienced noticeable fluctuations, reaching its peak on 10 July 2014, the highest level of the entire growing season. The abundance of precipitation, with an effective total of 140.6 mm, contributed to the increase in soil moisture content under all three mulching measures (CK, SM, and BM). CK had the lowest soil moisture content (13.95%), while SM and BM reached levels of 19.25% and 19.89%, respectively. Following this peak, the soil moisture content declined again until a subsequent rainfall event on August 6 increased the soil moisture content of CK, SM, and BM by 1.99%, 2.94%, and 2.53%, respectively. Afterward, SM and BM continued to consume a substantial amount of water as a result of the transpiration process of the jujube trees, while the level of effective precipitation noticeably declined. Along with the interception of precipitation by the surface mulching layer, the soil moisture content continued to decrease until 10 September, reaching its minimum values of 13.14% and 13.38% for SM and BM, respectively, throughout the growth season. CK, which had a bare soil surface, had its lowest point of 8.57% on 19 August due to significant soil water evaporation, but it fluctuated upward with the supplement of two effective precipitations. During the jujube tree's fruit ripening period from the middle to the end of September, transpiration diminished and soil water demand decreased. At the same time, there was a substantial increase in effective precipitation, approximately 70 mm. This led to an increase in soil water content. However, as the loess-hilly region entered the dry and rainless season, the soil's water content steadily decreased. Throughout the 2014 growing season, the soil moisture content in CK remained consistently low. Its average soil moisture content of 10.43% was significantly lower than that of SM and BM, with differences of 5.10% and 4.85%, respectively ($p < 0.05$).

During the sprouting and leaf spreading period, flowering and fruiting period, and the early stage of fruit expansion in the 2015 growing season, the soil moisture content of CK, SM, and BM showed a general decreasing trend (Figure 3B). By 1 August, the soil moisture content had declined by 2.75%, 2.74%, and 3.26% for CK, SM, and BM, respectively. This decrease can be attributed to the limited number of effective precipitation events during this period, totaling only 37.6 mm. As a result, the rainfall was insufficient to meet the evapotranspiration demands of the soil, resulting in continuous water loss from the soil. However, the soil moisture content under all three mulching measures experienced a significant increase following the supplementation of rainfall with a daily precipitation of 61 mm. As a result, the soil moisture content of CK, SM, and BM rose by 1.52%, 5.35%, and 5.79%, respectively. After reaching peak values, the soil moisture content under all three mulching measures exhibited a markedly declining pattern. The amount and frequency of precipitation increased dramatically after September 3, leading to the peak soil moisture contents of CK, SM, and BM on September 11, reaching 10.42%, 15.89%, and 13.76%, respectively. Subsequently, the amount of precipitation decreased, and under the influence of evapotranspiration, the soil moisture content under the three mulching measures declined to varying degrees. The soil moisture content of SM and BM was significantly higher than that of CK throughout the 2015 growing season ($p < 0.05$). Their average soil moisture content of 13.41% and 12.89% was 4.60% and 4.07% higher than CK, respectively. In contrast, the soil moisture content of CK was consistently low, almost at the wilting moisture level, and had an average soil moisture content of just 8.81%.

Comparing the 2015 growing season to the 2014 growing season, it is worth noting that the total amount of precipitation was 88.2 mm less in 2015 (Figure 3A,B). This significant decrease in precipitation resulted in significantly lower soil moisture content in the 2015 growing season under all three mulching measures ($p < 0.05$). Compared to the 2014 growing season, the soil moisture content of CK, SM, and BM declined by 1.61%, 2.12%, and 2.39%, respectively, in the 2015 growing season.

3.1.2. Vertical Variation Characteristics of Soil Moisture Content under Different Mulching Measures

In the growth season of the year with normal precipitation (2014), the soil moisture content in the 0–280 cm soil layer under the three mulching measures was higher compared to the growth season of the year with dry conditions (2015) (Figure 4A,B). CK, SM, and BM treatments showed an increase of 1.62%, 2.12%, and 2.39%, respectively, in the normal precipitation year. Among the three mulching measures, SM had the highest soil moisture content, followed by BM, while CK had the lowest soil moisture content during both the normal precipitation year and the drought year. Compared to CK treatment, SM and BM treatments experienced an increase of 5.09% and 4.84%, respectively, in soil moisture content during the normal precipitation year (Figure 4A). Similarly, in the dry year, the SM and BM treatments had an increase of 4.60% and 4.07%, respectively, in soil moisture content compared to the CK treatment (Figure 4B). These results indicate that both SM and BM mulching measures were effective in increasing soil moisture content in comparison to CK treatment, particularly during the year with normal precipitation. The SM treatment consistently showed the highest soil moisture content, highlighting its effectiveness in retaining soil moisture.

In the 0–280 cm soil layer, straw mulching had a significant impact on soil moisture content. During the normal precipitation year, the soil moisture content of SM in this soil layer was 2.64–9.58% higher than that of CK throughout the entire growing season (Figure 4A). Similarly, in the dry year, the soil moisture content of SM in the 0–280 cm soil layer was 1.81–9.71% higher than CK throughout the growing season (Figure 4B). On the other hand, jujube branch mulching mainly influenced the soil moisture content in the

40–100 cm and 220–280 cm soil layers. In the normal precipitation year, the soil moisture content of BM in the 40–100 cm and 220–280 cm soil layers was, on average, 7.15% and 7.80% higher than CK throughout the entire growing season (Figure 4A). Similarly, in the dry year, BM resulted in soil moisture content that was 6.01% and 7.73% higher than CK in the respective soil layers (Figure 4B).

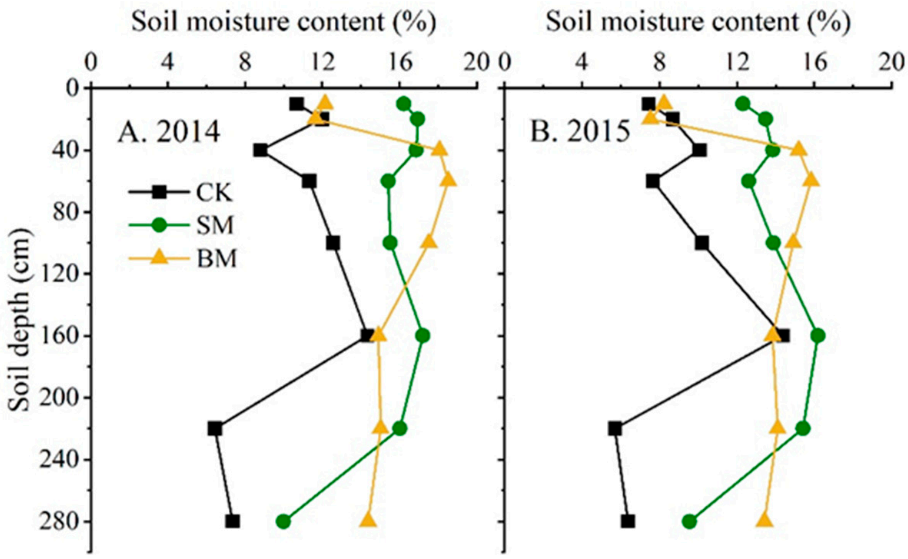

Figure 4. Vertical changes in soil moisture content in the experimental rain-fed jujube orchard under different mulching measures during the growth seasons of 2014 (**A**) and 2015 (**B**).

3.1.3. Variability of Soil Moisture under Different Mulching Measures

Figure 5 illustrates the coefficient of variation (C_v) of soil moisture content for the three mulching measures in different precipitation years. In the normal precipitation year, the C_v of soil moisture content in the 0–60 cm soil layer was lower for straw mulching (SM) and jujube branch mulching (BM) compared to the control treatment (CK) (Figure 5A). Specifically, the C_v of SM and BM in this soil layer was 14.44% and 13.16% lower than CK throughout the jujube growth season, respectively. However, at a depth of 100 cm, the C_v of SM and BM increased by 3.52% and 2.66%, respectively, compared to CK. In the 160–280 cm soil layer, the C_v of SM and BM decreased by 3.09% and 2.57%, respectively, compared to CK. During the dry year, in the 0–100 cm soil layer, both SM and BM had lower C_v values compared to CK (Figure 5B). Specifically, the C_v of SM and BM was lower than that of CK by 8.02% and 4.31%, respectively. However, at a depth of 160 cm, the C_v of SM and BM increased by 1.46% and 4.20%, respectively, compared to CK. In the 220–280 cm soil layer, the C_v of SM and BM was 7.54% and 4.87% lower, respectively, compared to CK. These findings indicate that both straw mulching (SM) and jujube branch mulching (BM) can increase the stability of soil water to varying degrees in rain-fed jujube orchards. SM exhibited a relatively higher level of soil moisture stability. The C_v of soil moisture content decreased as soil depth increased, indicating increased stability of soil water (Figure 5A,B). Moreover, as soil depth increased, the difference in C_v of soil moisture content among different mulching measures also decreased, suggesting a diminishing impact of mulching measures on soil moisture content.

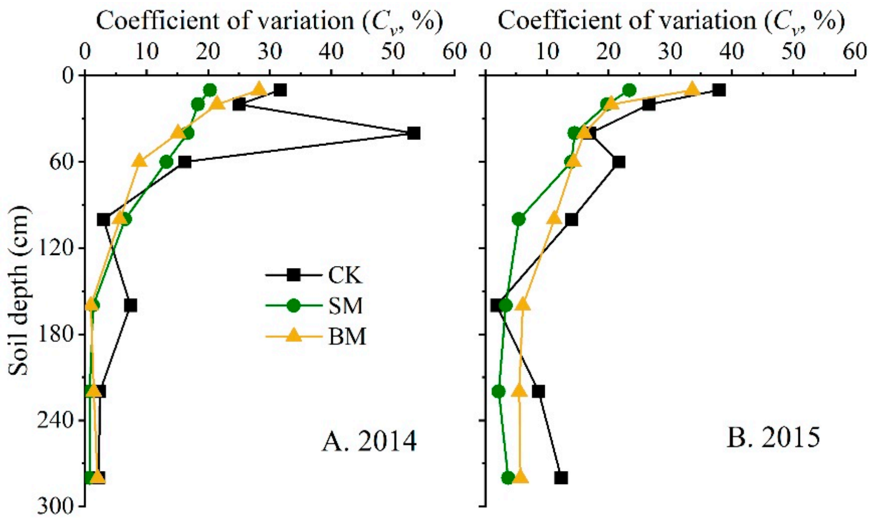

Figure 5. Vertical distribution of the coefficient of variation (C_v) of soil moisture in the 0–280 cm soil layer in the experimental rain-fed jujube orchard under different mulching measures during the growth seasons of 2014 (**A**) and 2015 (**B**).

3.1.4. Grey Relational Analysis of Soil Moisture under Different Mulching Measures

To investigate the profile characteristics of soil moisture under various mulching measures, we employed the gray relational method to evaluate the gray relational grades of soil moisture in different soil layers. The soil profile was divided into four layers: the surface layer (0–20 cm), the root layer (>20–100 cm), the sub-deep layer (>100–180 cm), and the deep layer (>180–280 cm). We collected monthly average soil moisture content data from May to October for each layer: $x_1 = \{x_1(k) \mid k = 5, 6, \ldots, 10\}$, $x_2 = \{x_2(k) \mid k = 5, 6, \ldots, 10\}$, $x_3 = \{x_3(k) \mid k = 5, 6, \ldots, 10\}$, and $x_4 = \{x_4(k) \mid k = 5, 6, \ldots, 10\}$. In this analysis, the surface layer was used as the reference sequence, while the root layer, sub-deep layer, and deep layer were employed as comparison sequences. The corresponding gray relational grades were recorded as R_{12}, R_{13}, and R_{14}, respectively. Similarly, the root layer served as the reference sequence, while the sub-deep layer and deep layer acted as comparison sequences, with the gray relational grades recorded as R_{23} and R_{24}, respectively. Finally, the sub-deep layer was the reference sequence, the deep layer served as the comparison sequence, and the gray relational grade was recorded as R_{34}. The gray relational grades of soil moisture in different soil layers under various mulching measures are summarized in Table 2.

Table 2. Grey relational grade of soil moisture in different soil layers under different mulching measures in the experimental rain-fed jujube orchard during the growth seasons of 2014 and 2015.

Experimental Year	Grey Relational Grade	Mulching Measures		
		CK	**SM**	**BM**
2014	R_{12}	0.6306	0.7409	0.7255
	R_{13}	0.5371	0.6702	0.6340
	R_{14}	0.4906	0.6100	0.4804
	R_{23}	0.6872	0.6886	0.6745
	R_{24}	0.5367	0.6420	0.6145
	R_{34}	0.7545	0.9527	0.8413
2015	R_{12}	0.6468	0.8289	0.7334
	R_{13}	0.4663	0.7123	0.6804
	R_{14}	0.4568	0.4886	0.4473
	R_{23}	0.7329	0.7797	0.7240
	R_{24}	0.4524	0.6322	0.5128
	R_{34}	0.7469	0.9328	0.9246

Similar trends were observed in the CK, SM, and BM treatments, indicating a strong association between soil moisture in the surface layer and the root layer, followed by the sub-deep layer, and finally the deep layer, which exhibited the weakest relationship (Table 2). This suggests that soil moisture in the root layer primarily originates from surface seepage, with precipitation-induced surface seepage directly reaching the root layer while only a small amount infiltrates deeper layers (below 100 cm). The soil moisture content of the root layer showed a close relationship with that of the sub-deep layer, indicating a stronger association between these layers compared to the surface layer and the sub-deep layer. This highlights that soil moisture in the sub-deep layer is predominantly derived from secondary seepage originating in the root layer, with a lesser contribution from soil moisture in the surface layer. It further elucidates that the root layer acts as a necessary intermediary for the sub-deep layer's soil moisture replenishment. Moreover, in the CK treatment, the correlation between the root layer and the sub-deep layer was stronger than the correlation between the surface layer and the root layer. This implies that secondary seepage has a greater impact on soil moisture dynamics than primary seepage. Conversely, in the BM and SM treatments, the gray relational grade (R_{12}) was higher than the R_{23} grade, contrasting the previously mentioned trend. This suggests that primary seepage in BM and SM has a more notable influence on soil moisture compared to secondary seepage.

The comparison of soil moisture changes between the surface layer and the root layer under different mulching measures revealed that the closest similarity was observed in the SM treatment, followed by BM, while CK showed the least similarity (Table 2). This indicates that the trend of soil moisture in the surface layer and the root layer varied depending on the mulching approach employed. The research findings demonstrated that surface seepage had diverse effects on soil moisture recharge in the root layer depending on the type of mulching used. The closest proximity in soil moisture change between different soil layers was found in the SM treatment, followed by BM, while CK exhibited the least proximity. This suggests that both straw mulching and jujube branch mulching, in comparison to clean tillage, exerted noticeable regulating effects on soil moisture throughout the soil profile. Particularly, straw mulching had a relatively deep regulatory effect, resulting in a relatively mild change in soil moisture across the vertical profile. Consequently, it is evident that different mulching measures yield varying outcomes in soil moisture fluctuations across various soil layers.

3.2. Effects of Different Mulching Measures on Soil Temperature

3.2.1. Variations in Daily Average Soil Temperature across Different Soil Layers

The daily average soil temperature in the jujube orchard, under both surface mulching measures (straw mulching and jujube branch mulching), followed a similar trend to that observed in the absence of mulching (Figure 6). As the growing season progressed, the soil temperature exhibited an initial rise followed by a subsequent decline. Significant variations in soil temperature were observed in the surface layer, with a slower change in temperature as the soil depth increased but still exhibiting a single peak. Gradual increases in soil temperature occurred during the budding and leafing stages, as well as the flowering and fruiting stages (early May to mid-July).

The soil temperature in the SM and BM treatments was lower compared to the CK treatment (Figure 6). This can be attributed to the interlayer created by the straw and jujube branches on the soil surface, which blocked direct sunlight and ground radiation, absorbing them and reducing heat and moisture exchange between the soil and air. In the 0–10 cm soil layer, the soil temperatures of SM and BM decreased by 5.86% and 3.76%, respectively, compared to CK during the 2014 growing season (Figure 6a–c), and by 8.12% and 4.91%, respectively, during the 2015 growing season (Figure 6d–f). The temperature difference between covered and uncovered soils decreased with increasing depth in the soil layer (Figure 6). At a depth of 100 cm, the soil temperature of SM was only 3.97% and 5.50% lower than that of CK in the 2014 and 2015 growing seasons, respectively (Figure 6b,e). In contrast to CK, BM did not exhibit a decrease in soil temperature in the 60–100 cm soil layer throughout the two growth seasons (Figure 6c,f). In both the growth seasons of 2014 and 2015, soil temperatures reached their peak in early August (Figure 6). Prior to the conclusion of the fruit expansion stage (early September), the soil temperature in the shallow layer was higher than that in the deep layer. Specifically, the temperature values followed this order: 10 cm > 20 cm > 40 cm > 60 cm > 100 cm. However, after the fruit expansion stage, both air temperature and solar radiation rapidly decreased, leading to a decrease in the soil temperature of the shallow layer. Due to the time-lag effect, the soil temperature in the deeper layer gradually increased, exhibiting characteristics opposite to those of the earlier period. During this stage, the soil temperature in the 10–100 cm soil layer dropped by 2.83–10.08%, indicating that mulching had a cooling impact (referred to as SM; Figure 6b,e). On the other hand, mulching with branches (referred to as BM) had a negligible warming effect, increasing soil temperatures in the 10–100 cm soil layer by 1.45–3.06% in the 2015 growing season (Figure 6f). In the growth season of 2014, the warming effect of BM was observed at depths of 20 cm, 40 cm, and 100 cm, with increases of 0.75%, 0.13%, and 0.04%, respectively (Figure 6c). Based on these findings, it can be inferred that mulching jujube branches had a cooling impact on the soil during the early and middle stages of the jujube growth period, while it had a slight warming effect during the late stage.

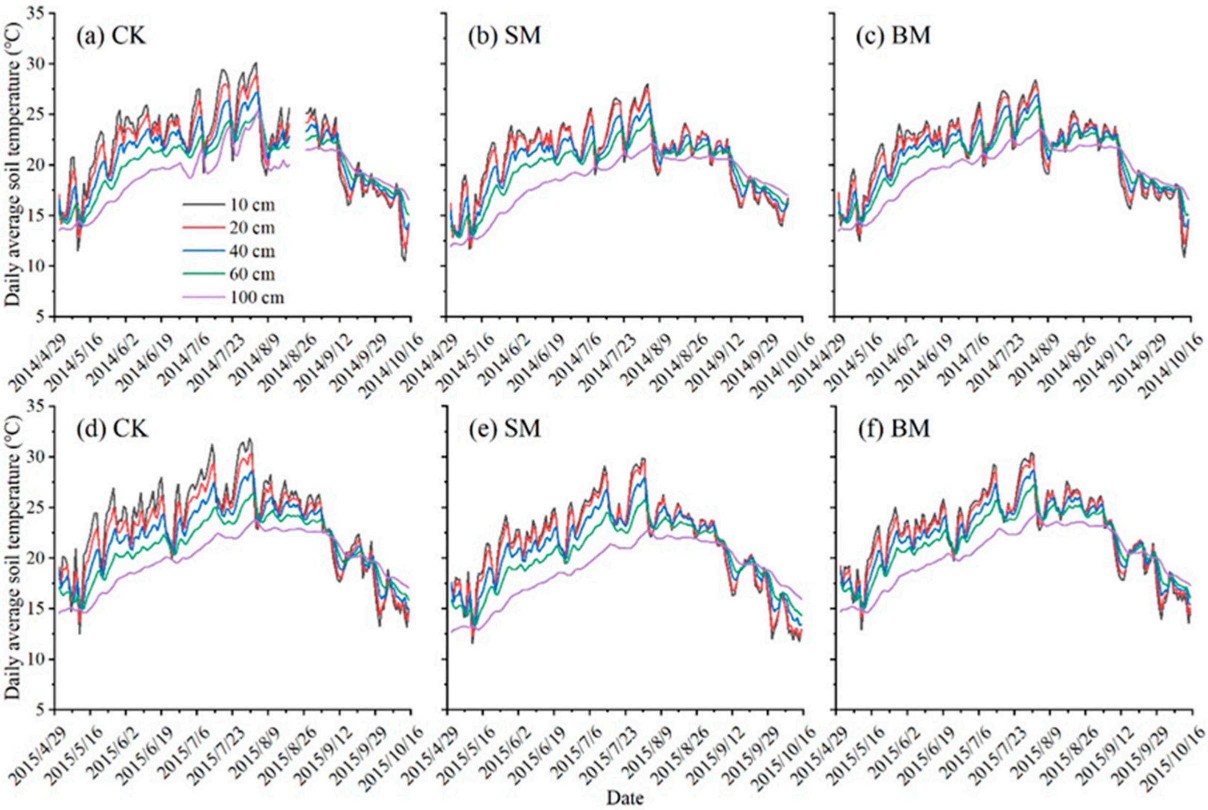

Figure 6. Dynamic fluctuations in daily average soil temperature at different depths of 0−100 cm in the experimental rain-fed jujube orchard under CK (**a**), SM (**b**), and BM (**c**) treatments, during the 2014 growing season, as well as under CK (**d**), SM (**e**), and BM (**f**) treatments during the 2015 growing season.

3.2.2. Analysis of the Daily Range of Soil Temperature

In both the growing seasons of 2014 and 2015, the daily range of soil temperature and its variation range in the jujube orchard were consistent across the three mulching measures: CK, BM, and SM (Table 3). The order of the temperature range was as follows: 10 cm > 20 cm > 40 cm > 60 cm > 100 cm. Notably, these ranges were lower than those for the air temperature. In the 2014 growing season, CK exhibited the largest daily range and variation range of soil temperature, followed by BM, while SM had the smallest ranges. Specifically, at depths of 10 cm, 20 cm, and 40 cm, the soil temperature's daily range in CK was 2.24 °C, 1.89 °C, and 0.36 °C higher than that of SM, respectively. Similarly, the daily range in CK was 1.15 °C, 1.23 °C, and 0.22 °C higher than that of BM at the aforementioned depths. No significant difference was found in the daily range of soil temperature between SM and BM in the 60–100 cm soil layer ($p > 0.05$), and both measures were 0.01–0.05 °C lower than CK. Analyzing the 0–100 cm soil layer throughout the 2015 growth season, the daily range of soil temperature and its variation range indicated that CK > BM > SM. Specifically, at depths of 10 cm and 20 cm, the daily range of soil temperature in CK was 2.52 °C and 1.96 °C greater than that of SM and 0.97 °C and 0.90 °C higher than that of BM, respectively. At a depth of 40 cm, the daily range of soil temperature in CK was 0.40 °C greater than that in SM but not significantly different from that in BM ($p > 0.05$). At a depth of 60 cm, there was no statistical difference in the daily range of soil temperature between SM and BM ($p > 0.05$); however, both measures were significantly lower than CK ($p < 0.05$). Lastly, at a depth of 100 cm, all three mulching measures resulted in a limited daily range of soil temperature, ranging from 0 to 0.02 °C.

3.2.3. Vertical Variation Characteristics of Soil Temperature

Despite the different mulching measures employed, the vertical variation characteristics of soil temperature in the jujube orchard remained consistent (Table 4). As the soil depth increased, both the amplitude and variation degree of soil temperature exhibited a steady reduction. In the surface layer of CK during the 2014 jujube growth season, the changing amplitude (K_a) and variation degree (C_v) of soil temperature were higher compared to the treatments with mulching measures. Conversely, the surface layer of SM had the lowest changing amplitude and variation degree of soil temperature. The middle layer soil temperature changes in both SM and BM had an amplitude of approximately 1.87 °C, which was smaller than that of CK. Regarding the degree of variation, CK experienced the largest variation, followed by BM, while SM had the lowest. In the deep layer, the changing amplitude of soil temperature followed the pattern K_a(SM) < K_a(BM) < K_a(CK), and the variation degree showed a similar pattern with values of C_v(SM) < C_v(BM) < C_v(CK). Analyzing the changing amplitude of soil temperature in the surface layer and deep layer over the 2015 jujube growing period, it was observed that K_a(SM) < K_a(BM) < K_a(CK), which was consistent with the pattern observed for the variation degree. The middle layer of SM had the lowest changing amplitude of soil temperature, followed by BM with a slightly greater change and CK with the largest change. The C_v of soil temperature in the middle layer of both SM and BM was consistent, with both measures being 14.4%, significantly lower than that of CK. In summary, mulching with straw and jujube branches during the jujube growth seasons in both 2014 and 2015 proved effective in minimizing the changing amplitude and variation degree of soil temperature in the 0–100 cm soil layer of rain-fed jujube orchards. The impact of straw mulching was more pronounced in this regard.

Table 3. Daily range of soil temperature (°C) at different depths with different mulching measures in the experimental rain-fed jujube orchard throughout the growth seasons of 2014 and 2015.

Experimental Year	Mulching Measures	Soil Depth										Daily Range of Air Temperature	
		10 cm		20 cm		40 cm		60 cm		100 cm			
		Variation Range	Mean	Variation Range	Mean	Variation Range	Mean	Variation Range	Mean	Variation Range	Mean	Variation Range	Mean
2014	CK	0.99–9.45	4.96 ± 1.82 a	0.67–6.00	3.31 ± 1.08 a	0.41–2.98	1.03 ± 0.36 a	0.11–1.25	0.41 ± 0.23 a	0.04–0.52	0.18 ± 0.11 a	0.90–22.20	11.17 ± 4.28
	SM	0.56–4.94	2.72 ± 0.84 b	0.56–3.58	1.42 ± 0.46 b	0.28–2.69	0.67 ± 0.33 b	0.04–1.11	0.36 ± 0.22 b	0.04–0.38	0.15 ± 0.08 b		
	BM	0.63–7.48	3.81 ± 1.29 c	0.57–4.07	2.08 ± 0.64 c	0.27–2.82	0.81 ± 0.35 c	0.10–1.17	0.39 ± 0.21 b	0.04–0.49	0.17 ± 0.10 ab		
2015	CK	1.33–9.48	5.73 ± 1.90 a	1.09–5.99	3.67 ± 1.12 a	0.57–3.05	1.21 ± 0.32 a	0.19–1.34	0.46 ± 0.21 a	0.03–0.50	0.17 ± 0.11 a	1.21–18.39	10.63 ± 3.38
	SM	0.92–6.06	3.21 ± 0.93 b	0.96–3.80	1.71 ± 0.45 b	0.35–2.18	0.81 ± 0.28 b	0.10–1.22	0.38 ± 0.20 b	0.04–0.39	0.15 ± 0.08 b		
	BM	1.22–8.24	4.76 ± 1.52 c	1.02–5.16	2.77 ± 0.75 c	0.44–2.77	1.16 ± 0.34 a	0.12–1.20	0.39 ± 0.19 b	0.05–0.44	0.17 ± 0.10 a		

Note: The data is presented, mean ± standard deviation. Different lowercase letters within the same column indicate significant differences in daily range of soil temperature at a significance level of 0.05 for the same experimental year and soil depth under different mulching treatments.

Table 4. Characteristics of soil temperature change in the 0–100 cm profile of the experimental rain-fed jujube orchard over the growth seasons of 2014 and 2015 under different mulching measures.

Soil Layer	Variation Eigenvalue	Mulching Measures 2014			Mulching Measures 2015		
		CK	SM	BM	CK	SM	BM
Surface layer (0–20 cm)	K_a	2.646	2.331	2.429	2.481	2.22	2.366
	C_v/%	18.5	16.3	16.7	19.4	16.6	18.0
Middle layer (20–60 cm)	K_a	1.968	1.870	1.865	2.026	1.853	1.884
	C_v/%	14.8	14.2	14.5	16.2	14.4	14.4
Deep layer (60–100 cm)	K_a	1.871	1.748	1.850	1.796	1.636	1.666
	C_v/%	14.5	13.7	14.1	15.4	13.0	13.5

3.2.4. Response of Soil Temperature to Air Temperature

The study found that variations in air temperature were the primary factor influencing changes in soil temperature. The relationship between air temperature and soil temperature was analyzed in different soil layers: the surface layer (0–20 cm), the middle layer (>20–60 cm), and the deep layer (>60–100 cm) using daily average soil temperature data. In the surface layer of the jujube orchard under the three mulching measures during the growing seasons of 2014 and 2015, the determination coefficient (R^2) between air temperature and soil temperature ranged from 0.72 to 0.87, indicating a strong correlation (Figure 7). The highest R^2 values in the middle and deep layers were indeed 0.58 and 0.21, respectively. On the other hand, the lowest R^2 values in the middle and deep layers were 0.43 and 0.10, respectively. These values demonstrate that as soil depth increased, the correlation between air temperature and soil temperature decreased, indicating a diminishing impact of air temperature on soil temperature. The R^2 between air temperature and soil temperature in the deep layer was found to be less than 0.21, indicating a very weak reaction between soil temperature and air temperature in this layer. This can be attributed to the heating of the surface soil layer by solar radiation, which then transfers heat through conduction and convection to the deeper soil layers. The heat gradually diminishes with increasing soil depth, resulting in a decrease in soil temperature. Thus, changes in air temperature primarily impact the surface soil layer, while the deep soil layer is minimally affected. When comparing the effects of the three mulching measures on the response of soil temperature to air temperature in the jujube orchard during the growing seasons of 2014 and 2015, it was observed that the R^2 values of air temperature and soil temperature in the surface layer were above 0.81 for CK, indicating a strong relationship (Figure 7a,d). However, the R^2 values for SM were weaker, not exceeding 0.79 (Figure 7b,e). BM also had weaker R^2 values compared to CK, with values around 0.76 in the 2014 season and slightly improving to 0.84 in the 2015 season (Figure 7c,f). Overall, CK exhibited a stronger correlation between air temperature and soil temperature in the surface layer compared to the other mulching measures (Figure 7a,d).

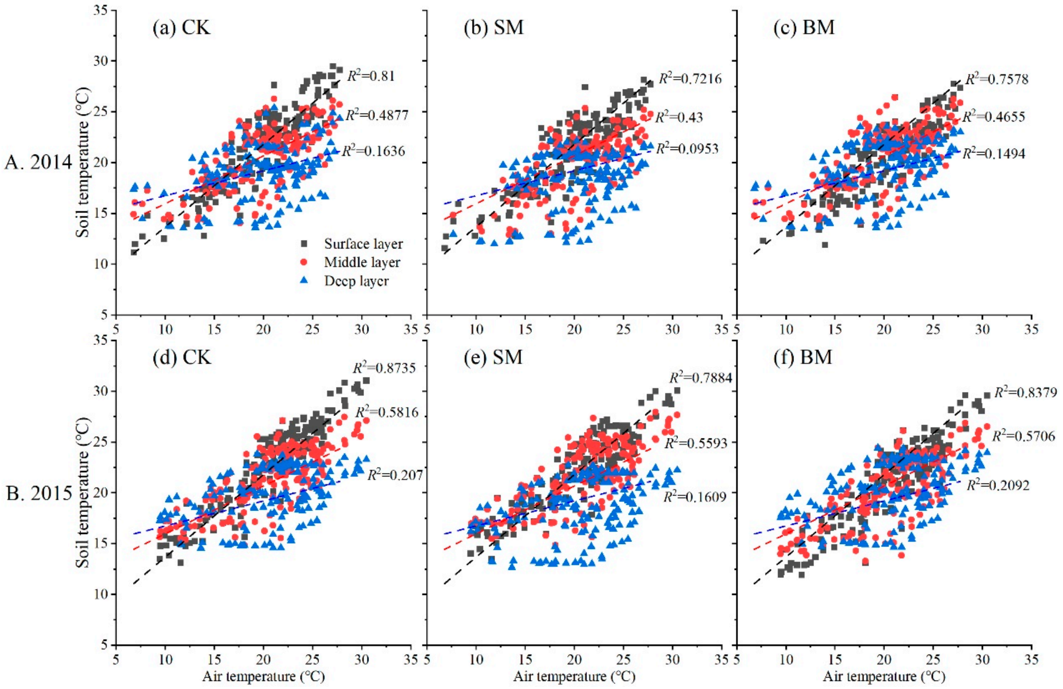

Figure 7. Statistical correlation between air temperature and soil temperature at different depths in the 0–100 cm profile of the experimental rain-fed jujube orchard under different mulching measures during the growth seasons of 2014 (**A**) and 2015 (**B**).

4. Discussion

4.1. The Impact of Mulching Practices on Soil Moisture

Soil moisture status, which can be determined by the moisture content in the soil, influences the development, distribution, and evolution of vegetation [32,33]. The study found that mulching with straw and jujube branches improved soil moisture content in the rain-fed jujube orchards (Figures 3 and 4). This improvement was observed in both a normal precipitation year (2014) and a dry year (2015) when compared to clean tillage practices. One possible explanation for this improvement is that mulching with jujube branches and straw helps prevent soil water evaporation. Soil evaporation is a major pathway for inefficient soil moisture loss, influenced by environmental variables such as air temperature, humidity, and wind speed [34,35]. In recent years, the northwest region of China has experienced the impact of global warming, resulting in accelerated vegetation and surface water evaporation [36]. As a consequence, this has exacerbated the issue of soil moisture deficiency in the area. By covering the soil with straw and jujube branches, a natural protective barrier is created, reducing moisture interaction between the soil and the air. This, in turn, limits solar radiation reaching the soil surface, preventing soil evaporation and maintaining soil moisture [23,37]. Mulching with jujube branches and straw also facilitates precipitation penetration. When it rains, runoff and soil water infiltration are closely linked [38]. Raindrop erosion can destroy the surface soil structure, restricting soil pores and promoting surface runoff [39,40]. However, mulching the soil surface with straw and jujube branches prevents direct impact from raindrops, improves surface roughness, slows down surface runoff velocity, extends the water-soil interaction period, and enhances soil moisture infiltration [41,42]. Global warming has induced alterations in precipitation patterns, ultimately leading to a minor net augmentation in global precipitation. Nonetheless, it is worth noting that this trend has not been uniform across all regions. In arid and semi-arid areas specifically, there has been a discernible reduction in precipitation levels, consequently exacerbating drought conditions in these regions [43]. Straw mulching and jujube branch mulching are effective measures that can optimize the utilization of limited precipitation resources and enhance soil water storage. Additionally, mulching with jujube branches and straw enhances soil structure, an important factor in controlling soil moisture content. It has two primary effects on soil structure. Firstly, the mulch of straw and jujube branches reduces the erosive impact of precipitation on the soil and prevents soil compaction [44,45]. Secondly, by covering the soil surface, it reduces the transport and erosion of fine soil particles by runoff while promoting the accumulation of organic matter. This encourages the transformation of aggregates from small to medium particle size, leading to reduced soil bulk density and enhanced formation of capillary pores. As a result, soil water infiltration is improved, and soil water storage capacity increases [42,46–48].

Research conducted by Liu et al. [14] on rain-fed apple orchards on the Chinese Loess Plateau showed that straw mulching increased the soil's water retention capacity. Suo et al. [26] also found that straw mulching effectively enhanced the regulation capacity of soil reservoirs in rain-fed apple orchards in gully regions of the Loess Plateau, improving soil hydrology. Similarly, Wang et al. [49] demonstrated through simulation studies on rain-fed jujube orchards on the Loess Plateau that full ground mulching with jujube branches increased soil moisture content and storage while reducing runoff and sediment. In another study by Ma et al. [8], large-scale simulations of soil columns in loess hilly areas showed that mulching with tree branches improved soil moisture retention and prevented soil drying. The findings of this study align with earlier investigations, highlighting the importance of mulching in controlling soil water penetration and evaporation. Straw mulching was found to be more effective than jujube branch mulching in enhancing soil moisture conservation (Figures 3 and 4). This may be attributed to the higher water absorption capacity and smaller pores of maize straw when it covers the soil surface. By reducing surface runoff and extending precipitation infiltration time, straw mulching increases soil moisture through more effective water absorption and minimizes ineffective soil water evaporation [50,51]. In conclusion, both straw and jujube branch mulching techniques alter soil water permeability, reducing soil water evaporation and enhancing the utilization of precipitation by crops. Additionally, the reutilization of straw and pruned tree branches offers a viable solution to mitigate the adverse environmental effects triggered by their combustion, such as the exacerbation of greenhouse effects and the generation of smoggy weather. Overall, mulching with straw and jujube branches has the potential to improve water management, promote organic and sustainable agriculture, and enhance crop production. Furthermore, the maize straw utilized in this study was procured from nearby farmland surrounding the experimental jujube orchard, while the jujube branches were obtained from pruning the trees within the experimental orchard itself. In comparison to mulching materials like plastic film and gravel, both straw and jujube branches offer several advantages, including ease of handling, cost-effectiveness, and environmental friendliness. However, it is important to note that while the use of pruned jujube branches allows for immediate coverage, the application of straw mulching may require additional considerations. These include the collection, storage, and transportation of straw, which may involve additional time, labor, and associated costs. These factors should be taken into account when deciding which mulching method to implement.

4.2. Effects of Mulching on Soil Temperature

Soil temperature plays a crucial role in crop development, and mulching practices have been found to have significant effects on soil temperature regulation. Organic mulching measures, in particular, have been shown to have a heat-insulating and heat-preserving impact on the soil [52,53]. Organic mulches provide insulation to protect plants and crops from freezing damage during low-temperature periods. They also help in maintaining a steady soil temperature, preventing soil overheating, and reducing the risk of burns to plants and crops during high-temperature periods. The presence of organic mulch also helps prevent excessive evaporation of soil moisture during hot weather. Studies conducted by Wang et al. [54] investigated the effects of various organic mulching materials, such as pebbles, bark, garden waste, waterborne polyurethane organic covering pads, and phenolic resin organic covering pads, on soil temperature. They found that the effects of mulching measures on soil temperature varied with seasonality. Organic mulches generally increase soil temperature in the winter and decrease it in the summer. In the case of mulching with jujube branches in this study, it was found to have a cooling effect on soil temperature during the early and middle phases of jujube development but a warming effect during the later stages (Figure 6c,f). This is because organic mulch acts as a thermal insulation material, serving as a buffer medium that prevents direct solar radiation from reaching the soil surface. This insulation helps maintain a lower soil temperature during hot weather conditions. However, during cold weather, the organic mulch reduces the dissipation of heat from the soil, leading to a warming effect and providing heat preservation.

Indeed, various mulching materials can have different effects on soil temperature, as observed in studies [55]. This study revealed that although both jujube branch mulching and straw mulching are organic mulches, straw mulching consistently had a cooling effect on soil temperature throughout the jujube growth period (Figure 6b,e), while jujube branch mulching had a slightly warming effect towards the end of the growth period (Figure 6c,f). Furthermore, both straw mulching and jujube branch mulching were found to decrease the daily range of soil temperature in the 0–100 cm soil layer (Table 3). They reduced the amplitude of soil temperature changes, mitigated the vertical variability of soil temperature, and made it less responsive to changes in air temperature (Table 4 and Figure 7). However, straw mulching was more effective in maintaining the stability of soil temperature compared to jujube branch mulching (Tables 3 and 4). This is attributed to the fact that covering the soil surface with straw or jujube branches can prevent solar radiation from penetrating the soil and reduce the outward radiation of heat, thereby decreasing the exchange of water and heat between the air and soil [23,56]. Jujube branch mulching is less effective in inhibiting the movement of heat and moisture between the soil and air compared to straw mulching, likely due to the larger holes created by branches on the soil surface. Additionally, straw mulching has good water storage capabilities, effectively maintaining soil moisture (Figures 3 and 4). Soils with high moisture content tend to have slower temperature changes when exposed to the same amount of solar radiation energy. Similarly, when the soil radiates the same amount of heat outward, areas with high soil moisture content and specific heat capacity experience slower temperature decreases. This is because water has a high specific heat capacity [57,58]. In conclusion, mulching with straw and jujube branches can effectively regulate soil temperature and minimize fluctuations in soil temperature. In the context of global warming, where the frequency and intensity of extreme weather events like high temperatures and extreme cold are on the rise, the utilization of straw mulching and jujube tree branch mulching becomes particularly crucial. These measures effectively mitigate the potential harm inflicted upon crop root systems due to sudden fluctuations in soil temperature resulting from weather variability and extreme conditions. Consequently, the application of these practices proves highly beneficial for promoting the optimal growth and development of crops.

5. Conclusions

The application of straw mulching and branch mulching techniques has shown promising results in certain regions and orchards, highlighting their potential for practical implementation. However, their utilization in rain-fed, sloping jujube orchards located in Loess hilly regions is still at an early stage, presenting several uncertainties and challenges. Thus, the present study aimed to implement the straw mulching (SM) and branch mulching (BM) techniques in rain-fed jujube orchards situated in loess hilly regions. The results demonstrated that both SM and BM significantly increased the average moisture content of the 0–280 cm soil layer during the jujube growing season in normal precipitation (2014) and drought (2015) years ($p < 0.05$), compared to the uncovered treatment (CK). In 2014, SM improved soil moisture content across all layers, with increases ranging from 2.64% to 9.58% compared to CK. Similarly, in 2015, SM increased soil moisture content by 1.81% to 9.71% in the 0–280 cm profile compared to CK. BM only showed significant increases in moisture content in the 40–100 cm and 220–280 cm layers. Additionally, both SM and BM reduced the coefficient of variation of soil moisture, indicating improved water stability. In 2014, SM and BM decreased the coefficient of variation by 14.44% and 13.16% in the 0–60 cm layer and by 3.09% and 2.57% in the 160–280 cm layer, respectively. Similarly, in 2015, SM and BM decreased the coefficient of variation by 8.02% and 4.31% in the 0–100 cm layer and by 7.54% and 4.87% in the 220–280 cm layer, respectively. In conclusion, the study highlights the effectiveness of SM in enhancing water stability in the soil profile. SM consistently displayed a stronger correlation between changing soil moisture across different layers, followed by BM, while CK exhibited the least favorable trend. Both SM and BM have a regulating influence on soil moisture, with SM having a deeper reach and causing a more moderate change in moisture levels.

SM and BM treatments resulted in lower temperatures than CK within the 0–10 cm soil layer during the growth seasons of 2014 and 2015. The temperature difference between SM/BM and CK decreased with increasing soil depth. SM consistently cooled the soil temperature during the entire jujube growth period, while BM had a cooling effect before fruit expansion and some heat preservation effect after. As the soil layer deepened, the daily range and variation range of soil temperature decreased for all treatments. CK had the largest daily range and variation range, followed by BM, while SM had the smallest. Both SM and BM reduced temperature variation in the 0–100 cm soil layer, with SM having a stronger impact. The temperature of the 0–20 cm soil layer showed the strongest correlation with air temperature, which weakened with increasing soil depth. Notably, SM had the least reaction to changes in air temperature, as indicated by its lowest R^2 value in the relationship between soil temperature and air temperature.

In summary, the study has shown that both SM and BM effectively enhance soil moisture conditions and regulate soil temperature. However, SM was found to exhibit better performance in this regard. Based on the findings, it is recommended to implement straw mulching throughout the entire jujube orchard to maximize the improvement of soil moisture and thermal conditions if the collection, storage, and transportation of straw are relatively convenient and efficient. In cases where there are difficulties in the collection, storage, and transportation of straw, which require substantial manpower, resources, and high costs, it may be more practical to opt for on-site coverage using pruned jujube tree branches. However, further research is needed to explore the potential synergistic effects of combining straw mulching and branch mulching in improving soil moisture and thermal conditions for jujube tree growth. Additionally, it is important to investigate whether the combined effect of these techniques surpasses or diminishes the individual positive effects of straw and branch mulching on soil moisture and thermal conditions.

This research study focused on examining the impact of various mulching measures on soil moisture and temperature within controlled geographical conditions. However, in future studies, it is crucial to take into account the comprehensive effects of slope gradient, position, aspect, and other factors on soil moisture and temperature variations across the entire slope surface. Additionally, the study period only encompassed observations from normal precipitation years and drought years, excluding data from other precipitation patterns. Therefore, further research is necessary to supplement the study by investigating soil moisture and temperature variations under different precipitation regimes. This will enable a systematic and comprehensive analysis of the mechanisms behind water retention and temperature regulation for different mulching measures.

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Data Availability Statement: The data that supports this study cannot be publicly shared due to ethical or privacy reasons but may be shared upon reasonable request to the corresponding author if appropriate.

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

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