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Impact of Mulching on Soil Moisture and Sap Flow Characteristics of Jujube Trees

Yi He [1,†], Zhikai Qiu [1,†], Rui Liu [1], Min Tang [1,*] and Pute Wu [2]

1 College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou 225009, China
2 Institute of Soil and Water Conservation, Northwest Agriculture & Forestry University, Xianyang 712100, China
* Correspondence: 007312@yzu.edu.cn
† These authors contributed equally to this work.

Abstract: The main purpose of this study was to assess the influence of grass planting and jujube branch mulching on soil moisture levels and jujube tree transpiration rates, with the ultimate goal of improving jujube tree production in rain-fed orchards. The study encompassed four treatments: jujube branch mulching (JBM), jujube branch mulching with white clover planting (JBM + WCP), white clover planting (WCP), and clean cultivation (CC). During a two-year experiment, it was observed that the JBM treatment exhibited the highest capacity for moisture conservation. Specifically, it resulted in an average increase of 2.69% (in 2013) and 2.23% (in 2014) in soil moisture content compared with the CC treatment. The application of statistical analysis revealed significant differences ($p < 0.05$) between JBM and JBM + WCP, as well as highly significant differences ($p < 0.01$) between JBM and WCP in the year 2013. In 2014, JBM exhibited significant differences ($p < 0.01$) from both JBM + WCP and WCP. Between April and August, JBM exhibited the highest soil moisture content, followed by CC, with WCP showing the lowest levels. From September to October, JBM retained its status as the treatment with the highest soil moisture content, JBM + WCP ranked second, and CC experienced a decline and recorded the lowest soil moisture content. Under sunny conditions, all treatments showed a broad peak curve in the daily variation of sap flow velocity. In cloudy weather, a multi-peak wave-like curve was observed with similar trends across treatments. Between April and August, the monthly average sap flow velocity of JBM ranked the highest, followed by CC, while WCP showed the lowest velocity. During the period of September to October, JBM maintained its lead in sap flow velocity, while JBM + WCP rose to the second position, and CC's sap flow velocity dropped to the lowest level. JBM and WCP treatments showed significant differences ($p < 0.01$), and in 2014, JBM also had significant differences ($p < 0.05$) compared with JBM + WCP. The sap flow velocity was positively correlated with air temperature, vapor pressure deficit, wind velocity, photosynthetically active radiation, and soil temperature. Photosynthetically active radiation was identified as the main driving factor influencing jujube tree transpiration. In conclusion, the findings of this study demonstrate the effectiveness of using pruned jujube branches for coverage in rain-fed jujube orchards. This approach not only conserves mulching materials and diminishes the expenses associated with transporting pruned jujube tree branches away from the jujube orchard but also achieves multiple objectives, including increasing soil moisture, promoting jujube tree transpiration, and enhancing soil water utilization. These results have significant implications for the efficient utilization of rainwater resources in rain-fed jujube orchards and provide valuable insights for practical applications in orchard management.

Keywords: rain-fed jujube trees; grass planting; branch mulching; soil moisture; sap flow; transpiration

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1. Introduction

The jujube (*Ziziphus jujuba* Mill.) tree, originating in China, possesses a remarkable cultivation history of over 5000 years [1]. Known for its resilience to drought and adaptability to arid conditions, the jujube tree thrives in regions with limited water availability, maintaining steady growth even during dry periods [2,3]. Additionally, jujube fruits are abundant in nutrients [4], boasting a delightful taste [5] and a high sugar content [6]. Consequently, not only do jujube trees contribute to a thriving industry, but they also play a significant role in improving the ecological environment. They are instrumental in preserving the stability of delicate ecosystems and aiding in the recovery and reconstruction of impaired ones [7,8]. China's policy on farmland conversion to forests since 1999 has brought about the emergence of expansive mountain jujube eco-economic forests [9]. Notably, the cultivation area of jujube trees in the northern region of Shaanxi Province alone has expanded impressively to cover 125,000 hectares [10]. As a result, this sector has become a vital pillar in the region's economy, serving as the primary source of income for farmers and making substantial contributions to the agricultural sector as a whole in northern Shaanxi [11,12]. However, the prevalence of "clean cultivation" in rain-fed jujube orchards in China, resulting from traditional management practices and farmers' mindsets, has given rise to a range of issues [13,14]. These issues encompass soil structure degradation, deterioration of physical and chemical properties, water and nutrient loss, reduced drought resistance in jujube trees, and low water use efficiency. As a consequence, not only does the current and future productivity of jujube orchards suffer, but the quality of jujube fruits also declines, thereby compromising their competitiveness in the market [15]. In order to address these challenges and ensure the sustainable development of the jujube industry, it is crucial to undertake a comprehensive assessment and make necessary adjustments to soil management practices.

Surface mulching is indeed a crucial soil management measure that serves multiple functions, including water conservation [16], temperature regulation [17], soil fertility enhancement [18], erosion control [19], and the regulation of micro-ecosystem environments. Because it creates favorable conditions for crop growth, it has been widely adopted as a soil management technique in various countries and regions [20–22]. In 1998, China introduced orchard surface mulching in the green fruit production system, drawing inspiration from successful practices in foreign countries. The nationwide promotion aimed to replace the traditional "clean cultivation" soil tillage method and promote water-saving practices in rain-fed orchards. The primary objective was to minimize soil moisture evaporation, effectively store and preserve moisture, and improve water use efficiency in orchards. However, despite these efforts, the majority of orchards in China still practice "clean cultivation," and surface mulching is implemented on a limited scale [23]. Exploring suitable surface mulching techniques, enhancing soil moisture conditions, improving water use efficiency, and maximizing the productive potential of natural precipitation are critical steps to optimize and upgrade the jujube industry. By addressing these aspects, continuous improvement in rain-fed jujube orchard ecosystems can be achieved. Moreover, these measures play a crucial role in promoting the overall development and sustainability of the jujube industry.

Currently, plastic film mulching and straw mulching are the two most extensively studied surface mulching measures, showcasing some progress [24,25]. However, these methods do come with drawbacks, such as soil pollution and increased pest and disease issues [26,27]. To address these concerns, branch mulching has emerged as a viable alternative to straw mulching, especially for orchards and ecological economic forests. Branch mulching offers advantages such as material savings, cost reduction, and easy implementation. Despite these benefits, research on branch mulching remains limited. Furthermore, research on grass planting in Chinese orchards has predominantly focused on fruit orchards with abundant rainfall, like citrus, pear, and longan orchards [28–30]. Only a few studies have delved into grass planting in apple orchards in the loess hilly region [31]. Additionally, there is a dearth of research on grass planting in rain-fed jujube orchards, which experience low and uneven annual rainfall. Moreover, due to variations in climate, fruit varieties, grass species, and soil types, research findings regarding the impact of grass planting on soil moisture in orchards across different regions have yielded inconsistent results [32,33]. Thus, further exploration is necessary to evaluate the applicability of grass planting in rain-fed jujube orchards. Moreover, ample research exists on sap flow characteristics and transpiration water consumption patterns in apple trees, peach trees, poplar trees, and other species [34–36]. However, limited research has been conducted on the transpiration water consumption patterns of jujube trees under different surface mulching measures in rain-fed orchards.

To address the aforementioned issues, this study introduces an innovative, diversified surface mulching pattern that includes grass planting, branch mulching, and their combinations. For the first time, we implemented diversified surface mulching in rain-fed jujube orchards, with the specific aim of thoroughly investigating the impact of different mulching patterns on key elements, such as soil moisture and jujube tree transpiration. Implementing this diversified mulching pattern will enable a comprehensive understanding of the benefits of various surface mulching patterns in managing rain-fed jujube orchards, thereby providing a scientific basis for soil quality and moisture management. Significantly, we conducted an in-depth study on the suitability of grass planting in rain-fed jujube orchards to address the research gap in this region regarding the suitability of grass planting in such orchards. Additionally, branch mulching was introduced as an innovative improvement measure, highlighting its advantages over traditional plastic mulching and straw mulching in rain-fed jujube orchards while also addressing the relatively limited research on branch mulching in this area. Through quantitative analysis based on simulated experiments, we thoroughly investigated the impact of different surface mulching patterns on the dynamics of soil moisture and the transpiration patterns of jujube trees. This scientific, rational, and optimized experimental design helps to accurately quantify the interactions between various factors, thereby providing a foundation for scientifically improving soil management. We believe that these innovative contributions will provide new theoretical and practical references for soil management and water resource utilization in rain-fed jujube orchards, promoting mutually beneficial development in economic and ecological aspects.

2. Materials and Methods

2.1. Experimental Design

2.1.1. Experimental Equipment

The study employed soil troughs as experimental plots, measuring 2.0 m in length, 0.8 m in width, and 0.8 m in height. These troughs were specifically designed with two sides constructed from transparent organic glass, enabling clear visibility of the interior. To maintain a balanced air pressure within the soil trough, the bottom was equipped with evenly spaced holes. This equilibrium in air pressure played a vital role in facilitating the unrestricted infiltration of soil moisture.

2.1.2. Experiment Materials

The jujube variety selected for this experiment was the Lizao, which was planted in the experimental plot on 20 November 2009. The initial average height of the plants was 24.5 cm. The experimental soil used was loessal soil sourced from Qingjian County, Yulin City, Northern Shaanxi Province, China. Prior to use, the soil was pretreated by passing it through a 10 mm sieve and naturally drying it until it reached a moisture content of approximately 5%. To facilitate soil moisture infiltration, a layer of gauze was placed at the bottom of the soil trough before filling it with soil. To ensure consistency with the field soil bulk density data provided by Gao et al. [37], the soil was maintained within the range of 1.35–1.40 $g \cdot cm^{-3}$. The soil trough was filled with seven layers of soil, each with a thickness of 10 cm, starting from the bottom. Additionally, the soil was compacted uniformly during the filling process. Moreover, before adding the next layer, the surface of the already-filled soil was scarified to minimize the negative impact of soil structure on water infiltration between soil layers. The main physical parameters of the experimental soil are outlined in Table 1.

Table 1. The main physical properties of the soil tested.

Particle Size (mm)	Content (%)	Saturated Hydraulic Conductivity (mm·min^{-1})	Saturated Moisture Content (%)	Field Capacity (%)	Wilting Coefficient (%)
<0.002 0.002–0.02 0.02–2	18.1 ± 2.6 64.3 ± 1.8 17.6 ± 1.3	0.49 ± 0.15	53.7 ± 1.9	29.4 ± 0.96	8.44 ± 1.32

Note: The data are presented in the form of mean value ± standard deviation.

The selection of white clover (*Trifolium repens* L.) as the grass species in this experiment was based on its specific ability to enhance nitrogen content in the soil through nitrogen fixation by its root system. White clover is a commonly used fine herbage in fruit orchards due to its known benefits in improving soil fertility [38]. In terms of root systems, the root system of white clover is mainly concentrated in the 10−20 cm depth of the soil [39]. On the other hand, the root system of the jujube tree has a higher distribution density in the 20−60 cm depth of the soil [40]. This distribution pattern allows the root systems of the grass (white clover) and the jujube tree to minimize overlap and thus reduces competition for water and nutrients between the two plants. White clover, a short grass variety, is highly suitable for dwarf and closely planted jujube orchards. It was sown on 5 March 2011, at a density of 15 g·m^{-2}. The experimental jujube branches were obtained from pruned jujube trees and crushed to a length of approximately 5−8 cm. These crushed branches were then utilized as mulch with a thickness of 10 cm. To ensure the successful establishment of both the jujube trees and the white clover, each plot received 4 kg of compound fertilizer with a nitrogen–phosphorus–potassium ratio of 18:12:10 prior to conducting the experiment. The soil's nutrient background values were measured before the application of fertilizer, yielding the following results: organic matter: 3.6 g·kg^{-1}, total nitrogen: 0.244 g·kg^{-1}, total phosphorus: 0.301 g·kg^{-1}, total potassium: 21.6 g·kg^{-1}, available nitrogen: 41.4 mg·kg^{-1}, available phosphorus: 4.6 mg·kg^{-1}, available potassium: 107.7 mg·kg^{-1}, and a pH level of 8.5. Consistent management practices were implemented across all experimental plots.

2.1.3. Experimental Plot Design

The study consisted of four distinct treatments, outlined as follows. (1) Jujube branch mulching (JBM): This treatment involved covering the entire experimental plot with jujube branches. (2) Jujube branch mulching with white clover planting (JBM + WCP): In this treatment, jujube branches were mulched in the central 80 cm area of the plot designated for jujube tree growth. Additionally, white clover was planted on both sides of this mulched area. (3) White clover planting (WCP): This treatment entailed the complete planting of white clover across the entirety of the experimental plot. (4) Clean cultivation (CC): Serving as the control group, this treatment did not incorporate any mulching throughout the duration of the experiment. Figure 1 provides a schematic diagram illustrating the layout corresponding to each treatment. Owing to constraints in the experimental site, available manpower, and budgetary limitations, we established two replicates for each treatment, resulting in two soil bins for each treatment.

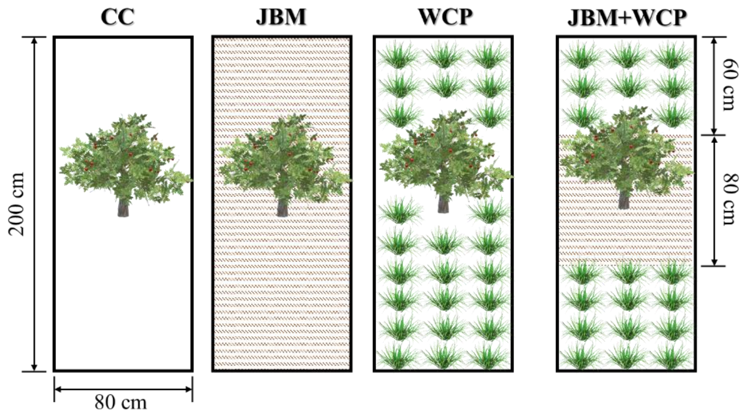

Figure 1. Schematic diagram of experimental treatments layout. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

To achieve consistent initial soil moisture levels in each experimental plot, the volumetric moisture content of the 0–65 cm soil layer was measured for all four treatments before the start of the experiments in March 2013 and 2014. On the basis of these measurements, the water storage was calculated. Subsequently, the treatment with the highest soil water storage was selected as the standard. The other three treatments were then irrigated quantitatively to supplement water, ensuring that their soil moisture levels were in line with the standard treatment. The irrigation was performed using a spouting pot to ensure uniformity. During the course of the 2013 experiment, a total rainfall of 319.8 mm was recorded. This rainfall was distributed as follows: 60.0 mm during the sprouting and leaf spreading period of the jujube trees (from mid-April to early May), 98.2 mm during the flowering and fruiting period (mid-May to mid-July), 115.9 mm during the fruit expansion period (late July to mid-September), and 45.7 mm during the fruit ripening period (late September to mid-October). In 2014, the total rainfall increased to 475.2 mm, with 86.1 mm occurring during the sprouting and leaf spreading period, 183.7 mm occurring during the flowering and fruiting period, 154.7 mm occurring during the fruit expansion period, and 50.7 mm occurring during the fruit ripening period. To minimize any potential distortion in the measured data caused by factors such as solar radiation, air temperature, and other variables influencing soil temperature and evaporation, white foam boards were embedded and bonded on both sides of the soil trough throughout the experiment. This insulation technique aimed to mitigate the aforementioned effects and ensure accurate observations.

2.2. Measurement Indicators and Methods

2.2.1. Soil Moisture

The volumetric moisture content of the soil in the 0–65 cm layer was determined using a CS830 neutron probe provided by Nanjing Chishun Technology Development Co., Ltd., Nanjing, China. Measurements were taken at depths of 5 cm, 15 cm, 25 cm, 35 cm, 45 cm, 55 cm, and 65 cm, with three measurements taken at each depth to calculate the average value. Soil moisture measurements were obtained from three locations within the experimental plot: one at the center and two on each side. These sampling points provided a representative assessment of the soil moisture levels across the entire experimental plot. Soil moisture measurements were collected from April 2013 to October 2014. Throughout the growing season, which spanned from April to October, weekly measurements were conducted, with additional readings carried out before precipitation events.

2.2.2. Sap Flow

The sap flow of jujube trees was continuously monitored using the TDP5 plant sap flow sensor provided by Beijing Yugen Technology Co., Ltd. (Beijing, China). The measurement method employed was the Thermal Dissipation Probe (TDP) method, which is based on the principle of thermal dissipation. The TDP method, developed by Granier in 1985 [41], is an improvement of the thermal pulse method, also known as the constant heat flux sensor method. In this method, a linear heating probe is inserted into the sapwood section of the tree trunk, with an unheated probe placed at a specific distance below it. As the sap flows through the trunk, heat from the heating probe is diffused upward, causing the probe to cool. By measuring the temperature difference (dT) between the heated and unheated probes, the sap flow velocity can be calculated. When the sap flow velocity is at its lowest or zero, the temperature difference between the probes reaches its maximum value. As the sap flow velocity increases, the thermal conductivity of the sapwood section also increases, resulting in a decrease in the temperature difference between the probes. Granier conducted calibration tests to establish a quantifiable relationship between the temperature difference and the sap flow velocity in the xylem. This relationship allows for the simple calculation of the tree trunk's sap flow velocity using the derived formula. The TDP method overcomes inherent systematic errors in transpiration volume determination and is less susceptible to external conditions, providing a more accurate measurement of sap flow in jujube trees.

The installation point for the probe on the jujube tree trunk was chosen to be approximately 10 cm from the base. Two boreholes were created in the same moisture channel for the placement of the probe. The probe was then wrapped with aluminum foil to ensure accurate measurements. The data collector used to capture the sap flow data was the RR-1016, manufactured by Beijing Yugen Technology Co., Ltd. The sampling interval was set to 120 s, and the average value was calculated and recorded every 10 min. The sap flow was measured using the continuous thermal diffusion principle proposed by Granier [41]. The thermal diffusion probe used consisted of two probes positioned 40 mm apart, with a probe diameter of 1.2 mm. The upper probe contained a constant heating element and a thermocouple. The heating resistance was 45 Ω, and the voltage was set to 1.25 V. The lower probe served as a reference terminal and only had a thermocouple. The sap flow velocity was determined by measuring the temperature difference between the two probes in the sapwood. The calculation of the sap flow velocity followed the empirical formula proposed by Granier [41]:

$$F_d = 118.99 \times 10^{-6} \left(\frac{\Delta T_{max} - \Delta T}{\Delta T}\right)^{1.231} \quad (1)$$

where F_d represents the volume of liquid flowing through the stem per unit area per unit time ($m^3 \cdot m^{-2} \cdot s^{-1}$); ΔT_{max} refers to the temperature difference (ΔT, °C) when the sapwood flow rate is zero. This condition typically occurs at dawn. Granier proposed that the best way to determine the maximum value, ΔT_{max}, is by analyzing all the temperature differences, ΔT, collected during each 7–10-day period [41]. In this specific study, the data processing methodology adopted involved identifying a single maximum value, labeled as ΔT_{max}, from the instantaneous temperature difference recorded every 7 days.

The daily cumulative sap flow (Q) of an individual tree is defined by Equation 2:

$$Q = \sum_{i=1}^{n} F_i \times A_s \times \Delta t \quad (2)$$

In this equation, the variable n represents the number of measurements taken per day, F_i refers to the sap flow velocity at the i-th sampling ($m^3 \cdot m^2 \cdot s^{-1}$), A_s denotes the sapwood area (m^2), and t represents the sampling interval time (s).

2.2.3. Sapwood Area

In the study, wood cores were drilled from the jujube tree trunk within each experimental plot, precisely at a point located 15 cm above the soil surface, employing a fine growth cone. The diameter of the trunk's heartwood and sapwood in the north–south direction was measured and averaged to determine the conducting area of the sapwood.

To estimate the sapwood area of the jujube trees across the entire experimental plot, a relationship equation between the sapwood area (A_s, mm^2) and the diameter at breast height (DBH, mm) was established. The equation used to establish this relationship is $A_s = 15.03 \times DBH - 102.69$, with an R^2 value of 0.916.

2.2.4. Meteorological Factors

In this study, meteorological data were collected from the Yangling National General Meteorological Station, situated approximately 200 m away from the experimental site. The data collection process involved recording four meteorological factors at a frequency of every 30 min. The meteorological variables that were collected included air temperature, relative humidity, wind speed, and photosynthetically active radiation.

Using the vapor pressure deficit (VPD) to reflect the combined effect of air temperature (T) and relative humidity (RH), the calculation formula is as follows [42]:

$$VPD = 0.611e^{\left(\frac{17.502T}{T+240.97}\right)}(1 - RH) \quad (3)$$

2.2.5. Statistical Analysis

The soil moisture content at a consistent depth within two soil bins for each treatment was subjected to averaging, while the sap flow velocities of two experimental jujube trees, also under the same treatment and assessed at the same time, were averaged. These averaged values were then used to represent the soil moisture content at the specified depth and the sap flow velocity of the jujube tree trunks for that particular treatment. One-way analysis of variance (ANOVA) with Tukey's post hoc test was performed to separate means at a significance level of $p < 0.05$.

3. Results

3.1. Influence of Grass Planting and Branch Mulching on Soil Moisture Condition in Jujube Orchards

3.1.1. Vertical Distribution of Soil Moisture under Grass Planting and Branch Mulching during the Critical Period of Jujube Tree Water Demand

During the month of May, jujube trees enter their flowering and fruiting period, which is highly dependent on water availability and crucial for achieving optimal yields. This period is known as the critical water period. Analyzing Figure 2, it is evident that in both experimental years, the JBM treatment consistently maintained obviously higher average soil moisture content in each layer (0–65 cm) compared with the other three treatments. On the other hand, the JBM + WCP and WCP treatments exhibited a lower soil moisture content in each layer compared with the CC treatment. The trend of the soil moisture content in the 0–65 cm soil layer among the four treatments exhibited a gradual increase from a depth of 0 cm to 45 cm, followed by a decrease from 45 cm to 65 cm. The JBM treatment consistently exhibited the highest average soil moisture content in the 0–65 cm layer among the three surface mulching patterns. In 2013 and 2014, the average soil moisture contents were 17.23% and 19.27%, respectively, which were 4.45% and 2.43% higher than those of the CC treatment. This indicates the strong water storage and moisture conservation capability of the JBM treatment. By contrast, the soil moisture content in the 0–65 cm soil layer of the WCP treatment remained generally low, particularly in the 0–20 cm layer. In 2013 and 2014, the average soil moisture contents were only 6.54% and 9.16%, respectively, which were lower than that of the CC treatment by 4.42% and 7.06%, respectively.

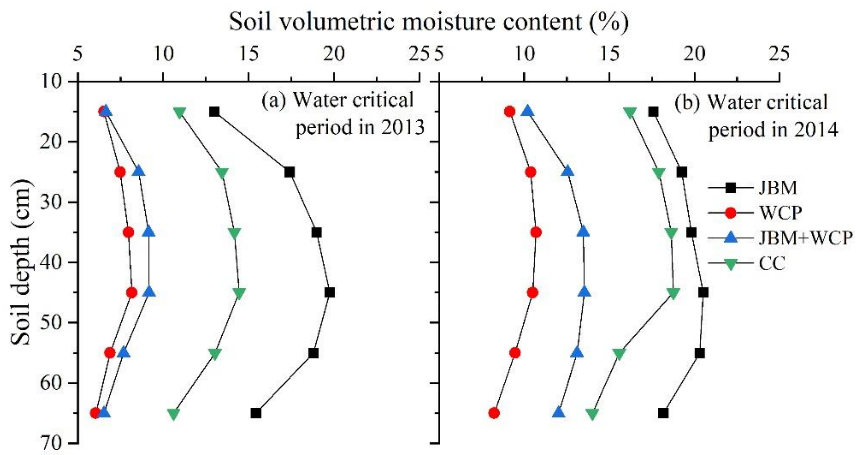

Figure 2. The vertical distribution of soil moisture content under different mulching treatments during the critical period of the jujube trees' water demand in May of (**a**) 2013 and (**b**) 2014. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

When comparing the soil moisture content in the 0–65 cm layer in May for the same treatment in two experimental years, there was a noticeable difference (Figure 2). In 2014, the soil moisture content of each treatment was obviously higher compared with that in 2013. The average increase was 2.04% for JBM, 4.52% for JBM + WCP, 4.07% for CC, and 2.56% for WCP.

According to the one-way ANOVA analysis conducted on the soil moisture content of the 0–65 cm layer in four treatments within the same experimental year, the following results were observed: in 2013, significant differences ($p < 0.01$) were found for all pairwise comparisons of treatments, except for a non-significant difference ($p > 0.05$) between the JBM + WCP and WCP treatments. This indicates that the soil moisture content differed significantly between all treatments, except for the JBM + WCP and WCP treatments, which showed no significant variation from each other. In 2014, significant differences ($p < 0.05$) were observed between the JBM and CC treatments as well as between the JBM + WCP and WCP treatments. Furthermore, all other pairwise treatments exhibited highly significant differences ($p < 0.01$), indicating significant variations in the soil moisture content for these treatments.

3.1.2. Vertical Distribution of Soil Moisture under Grass Planting and Branch Mulching during the Soil Water Storage Period

In September, the study area experienced an increase in rainfall and entered the rainy season. This resulted in decreased transpiration water consumption for jujube and white clover, as they entered the fruit ripening and withering stages, respectively. Lower solar radiation intensity and air temperature, along with increased relative humidity and decreased surface evaporation, also contributed to reduced soil moisture consumption and the onset of the water storage period in the soil. Comparing Figure 2 (representing May) with Figure 3 (representing September) in the same experimental year, it is clear that the soil moisture content of each layer in the 0–65 cm depth was higher in September. This increase was particularly notable in the JBM + WCP and WCP treatments. In September 2013, the average soil moisture contents in the 0–65 cm layer for the JBM, JBM + WCP, CC, and WCP treatments were recorded as 18.88%, 17.47%, 16.24%, and 17.25%, respectively (Figure 3a). These values exhibited increases of 1.65%, 9.52%, 3.46%, and 10.07% compared with the corresponding values observed in May (Figures 2a and 3a). In September 2014, the average soil moisture content in the 0–65 cm layer for the four treatments was measured at 23.54% (JBM), 18.08% (JBM + WCP), 17.04% (CC), and 17.50% (WCP) (Figure 3b). These values demonstrated increases of 4.27%, 5.61%, 0.19%, and 7.76% in comparison with the respective measurements recorded in May (Figures 2b and 3b).

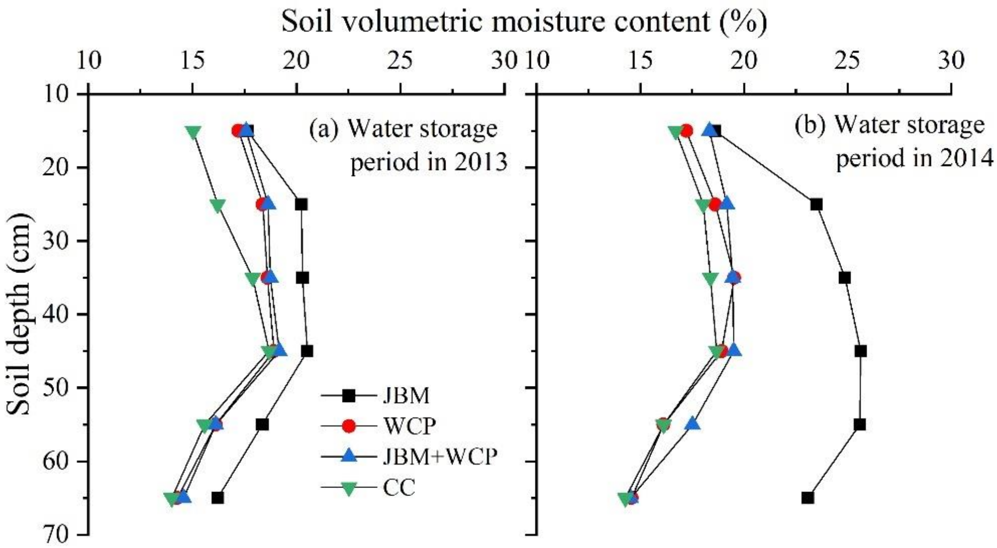

Figure 3. The vertical distribution of soil moisture content under different mulching treatments during the soil water storage period in September of (**a**) 2013 and (**b**) 2014. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

Throughout the experiment, the soil moisture content in the 0–65 cm layer in September followed the ranking JBM > JBM + WCP > WCP > CC (Figure 3). In 2013, a significant difference ($p < 0.05$) was observed between JBM and CC, indicating that the water storage capacity of jujube tree branches in the JBM treatment was superior to that in the CC treatment. In 2014, extremely significant differences ($p < 0.01$) were observed between JBM and JBM + WCP, CC, and WCP. This suggests that the JBM treatment exhibited the most stable and effective moisture conservation effect among the treatments.

3.1.3. Soil Moisture Retention Effect of Grass Planting and Branch Mulching

Figure 4 illustrates that throughout the entire growing season of the jujube trees in the two experimental years, different surface mulching measures displayed a similar overall trend in terms of water retention, resembling a 'W' shape. However, variations were observed in the characteristics of the soil moisture content under different treatments. During the sprouting and leaf spreading period of the jujube trees (from mid-April to early May), all four treatments exhibited obvious loss and a decrease in soil moisture content in the 0–65 cm soil layer. As the jujube trees entered the flowering and fruiting period (mid-May to mid-July), there was a notable increase in rainfall, leading to the initial restoration of soil moisture content. Subsequently, during the fruit expansion period (late July to mid-September), the vigorous growth of the jujube trees required substantial consumption of soil moisture. The relatively higher air temperature, lower relative humidity, and stronger soil evaporation during this period further exacerbated the decrease in soil moisture. During the fruit ripening period (late September to mid-October), the water consumption through transpiration by the jujube trees significantly decreased, and soil evaporation also weakened. Coupled with rainfall replenishment, the soil moisture content gradually increased, and the soil entered a period of water storage.

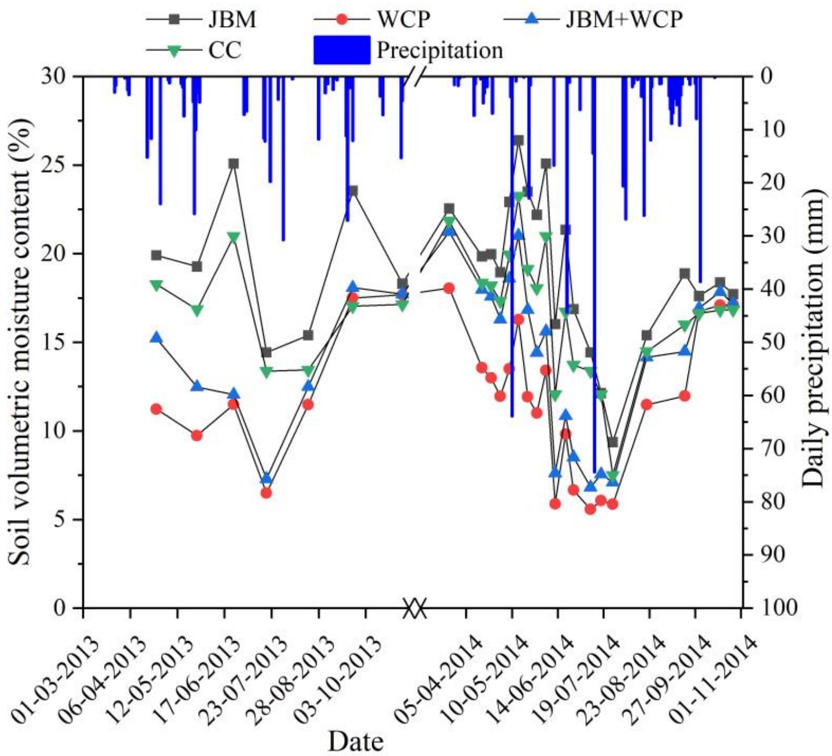

Figure 4. The variation of average soil moisture content in the 0–65 cm soil layer under different mulching treatments during the growing season. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

During the experiment, it was consistently observed that the JBM treatment maintained a higher level of soil moisture compared with the other three treatments (Figure 4). In 2013, the JBM treatment exhibited an average soil moisture of 19.42%, surpassing the JBM + WCP, WCP, and CC treatments by 5.80%, 7.19%, and 2.69%, respectively. Similarly, in 2014, the JBM treatment recorded an average soil moisture level of 18.98%, exceeding the JBM + WCP, WCP, and CC treatments by 4.59%, 7.16%, and 2.23%, respectively. This indicates that the JBM treatment effectively stored and preserved soil moisture. Generally, from April to August, the average soil moisture content in the 0–65 cm layer followed the order JBM > CC > JBM + WCP > WCP. The soil moisture contents of the JBM + WCP and WCP treatments were lower than that of the CC treatment. In 2013, the soil moisture contents were 4.67% and 6.49% lower than that of the CC treatment, and in 2014, they were 2.72% and 5.70% lower than that of the CC treatment, respectively. From September to October, the order shifted to JBM > JBM + WCP > WCP > CC. During this period, the soil moisture contents of the JBM + WCP and WCP treatments increased, surpassing that of the CC treatment. In 2013, they were 0.81% and 0.50% higher than that of the CC treatment, and in 2014, they were 0.56% and 0.23% higher than that of the CC treatment, respectively.

We conducted a one-way ANOVA analysis to compare the average soil moisture content in the 0–65 cm soil layer between the four treatments in the same experimental year. The ANOVA results demonstrated significant differences ($p < 0.05$) between JBM and JBM + WCP in 2013, as well as highly significant differences ($p < 0.01$) between JBM and WCP. Similarly, in the year 2014, highly significant differences ($p < 0.01$) were observed between JBM and JBM + WCP, as well as between JBM and WCP. Additionally, there were highly significant differences ($p < 0.01$) between CC and WCP. These findings suggest that the different treatments had a significant impact on the soil moisture content in the respective experimental years.

3.2. Effects of Grass Planting and Branch Mulching on the Sap Flow Characteristics of Jujube Tree Trunks

3.2.1. Diurnal Variations in Sap Flow of Jujube Tree Trunks

Due to the dense and diverse daily fluctuations in the sap flow velocity of jujube trees throughout their growth period, it is challenging to visually analyze and compare the specific dynamic characteristics of these daily variations. In order to overcome this challenge, we chose specific sunny and cloudy days in early, mid, and late July, which are critical periods for jujube tree growth. The classification of sunny and cloudy days in this study relied on observational assessments of weather conditions throughout the experimental period. Sunny days were characterized by a cloudless sky and abundant sunshine. On the contrary, cloudy days were identified by the presence of extensively layered clouds obstructing sunlight from reaching the ground, with the sun typically not visible due to the cloud cover. To ensure consistency, the jujube stem sap flow velocity for each treatment was averaged at the same time and on the selected date, taking into account the prevailing weather conditions. Following this procedure, we calculated the jujube stem sap flow velocity for the two selected weather days, along with the corresponding solar radiation data. These values were then plotted in Figures 5 and 6, providing a visual representation of the data.

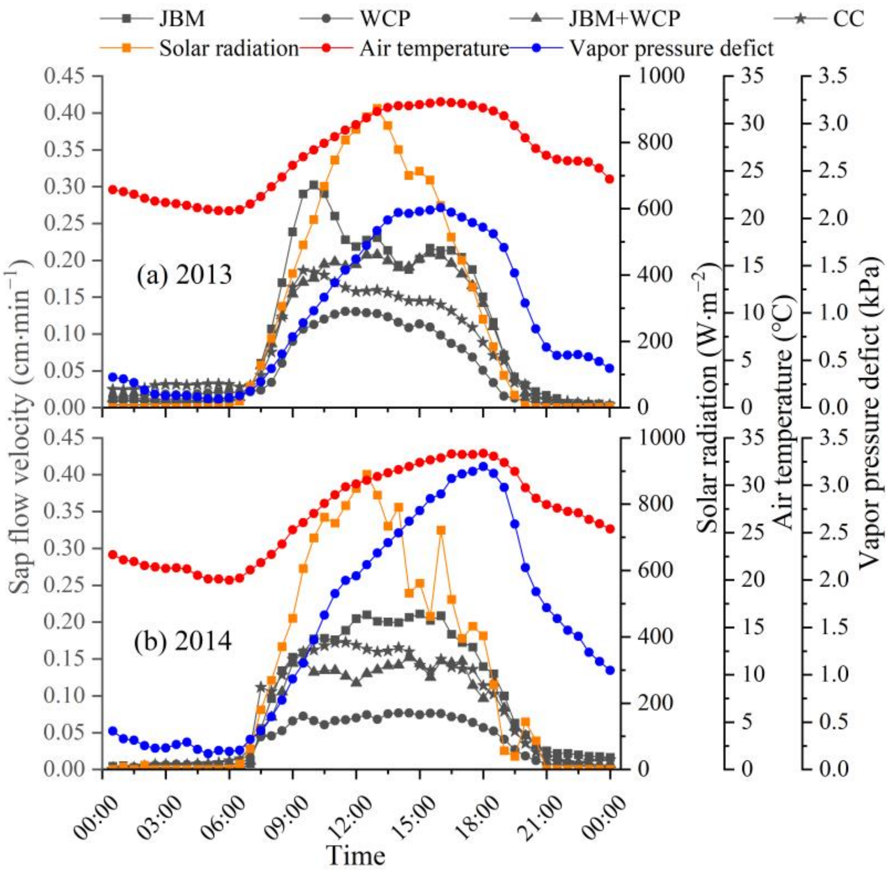

Figure 5. The daily variations of sap flow velocity in jujube tree trunks under different mulching treatments, as well as the daily variations in solar radiation, air temperature, and vapor pressure deficit on sunny days in (**a**) 2013 and (**b**) 2014. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

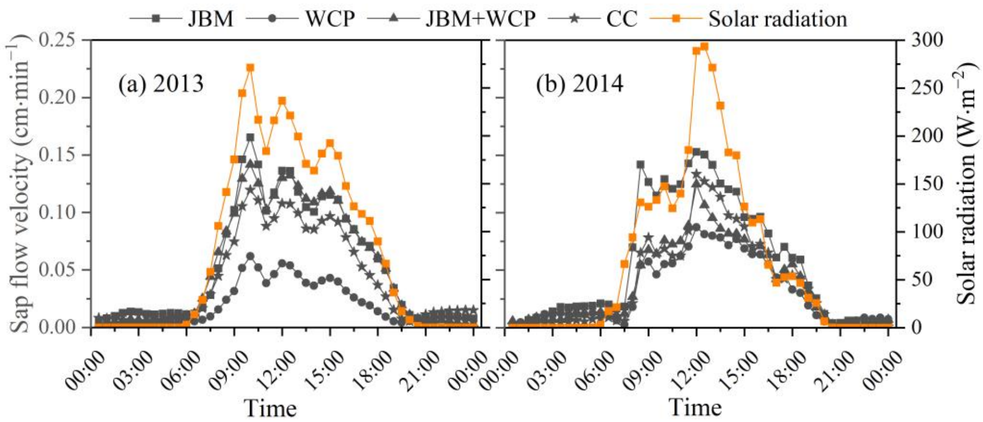

Figure 6. The daily variations of sap flow velocity in jujube tree trunks under different mulching treatments, as well as the daily variations of solar radiation, on cloudy days in (**a**) 2013 and (**b**) 2014. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

On the basis of the observations depicted in Figure 5, it is apparent that during both experimental years, the daily variation of jujube stem sap flow velocity in each treatment exhibited a characteristic broad peak-shaped curve under sunny conditions. The onset of stem sap flow in all four treatments occurred between 06:30 and 07:00, with a slight delay of approximately 0.5–1.0 h compared with the onset of solar radiation. As the solar radiation intensified, the air temperature gradually rose, leading to an increase in the vapor pressure deficit. Consequently, there was a continuous enhancement in stomatal conductance, leading to a rapid rise in stem sap flow velocity for each treatment. The peak velocity was reached around 09:30, followed by minor fluctuations, forming a plateau-like pattern with several small peaks.

The findings presented in Figure 6 demonstrate that during both experimental years, the diurnal variation curve of the sap flow velocity in each treatment under cloudy conditions exhibited similar patterns and closely corresponded to changes in solar radiation. Throughout the day, it displayed a multi-peak curve pattern while maintaining a relatively stable trend at night. In 2013, sap flow initiation for all four treatments occurred between 06:30 and 07:00 (Figure 6a). However, in 2014, there was a slight delay of approximately 0.5 h in the initiation time of sap flow for each treatment compared with 2013 (Figure 6a,b). Following the initial startup, there was a rapid increase in sap flow velocity. In 2013, the peak sap flow velocity for all treatments was observed around 10:00 (Figure 6a). In 2014, the peak velocity for each treatment occurred approximately 2.0 h later than in 2013 (Figure 6a,b). Subsequently, influenced by various meteorological factors, the sap flow velocity in each treatment displayed a fluctuating downward trend.

Table 2 provides the indicators that characterized the distinct features of the diurnal variation curves of the jujube stem sap flow velocity for each treatment on sunny and cloudy days during the two experimental years. From the perspective of stem sap flow initiation time, there was not much variation between sunny and cloudy days for the same treatment in 2013. However, in 2014, treatments on sunny days generally exhibited an earlier initiation time by approximately 1.0 h compared with treatments on cloudy days. Under sunny conditions in 2013, the peak time of the sap flow velocity in the four treatments was observed to be 20–40 min earlier compared with that on cloudy days. Additionally, the peak values of sap flow velocity were slightly higher than those observed on cloudy days. The treatments showed an increase in sap flow velocities compared with those observed under cloudy conditions, with respective increases for JBM (21.42%), CC (8.61%), JBM + WCP (31.57%), and WCP (28.42%). In 2014, under sunny conditions, the peak time of the sap flow velocity in each treatment occurred approximately 2.5 h earlier compared with cloudy days. Moreover, the peak values of sap flow velocity were higher than those observed on cloudy days. The treatments demonstrated an increase in sap flow velocities compared with those observed under cloudy conditions, with respective increases for JBM (8.80%), CC (6.89%), JBM + WCP (14.37%), and WCP (10.68%). In both 2013 and 2014, under cloudy conditions, the average daily sap flow velocity in each of the four treatments was lower than that on sunny days. The treatments displayed a decrease in sap flow velocity compared with those observed under sunny conditions, with respective decreases for JBM (48.45% in 2013, 37.54% in 2014), CC (41.94% in 2013, 51.40% in 2014), JBM + WCP (45.59% in 2013, 44.54% in 2014), and WCP (62.51% in 2013, 12.84% in 2014). Under sunny conditions, the rapid decrease in sap flow velocity and the end of transpiration in the four treatments actually occurred later thanthey did on cloudy days.

Table 2. The diurnal variation characteristics of sap flow in jujube tree trunks under different mulching treatments on sunny and cloudy days.

Year	Weather	Treatment	Starting Time	Peak Time	Peak Value ($cm \cdot min^{-1}$)	Daily Average Sap Flow Velocity ($cm \cdot min^{-1}$)	Time of Rapid Decline	End Time
2013	Sunny day	JBM	6:20	9:10	0.2835a	0.1054a	17:50	20:30
		WCP	7:00	9:30	0.1102b	0.0524b	17:50	19:30
		JBM + WCP	7:00	9:30	0.1937c	0.0785a	17:50	20:20
		CC	6:40	9:20	0.1940c	0.0902a	17:50	20:30
	Cloudy day	JBM	6:40	9:50	0.2335a	0.0544a	14:50	20:00
		WCP	7:10	9:50	0.0858b	0.0196b	14:50	19:10
		JBM + WCP	7:00	9:50	0.1472c	0.0427a	14:50	19:20
		CC	6:20	9:50	0.1787d	0.0524a	14:50	20:30
2014	Sunny day	JBM	6:30	9:30	0.1773a	0.0910a	18:10	20:50
		WCP	6:40	9:20	0.0727b	0.0363b	18:10	20:50
		JBM + WCP	6:40	9:10	0.1612c	0.0676a	18:20	20:50
		CC	6:40	9:30	0.1636c	0.0781a	18:10	21:00
	Cloudy day	JBM	7:20	12:00	0.1630a	0.0569a	14:30	20:20
		WCP	7:20	12:00	0.0657b	0.0317b	14:30	20:20
		JBM + WCP	7:10	12:00	0.1409c	0.0375b	14:30	20:30
		CC	7:30	12:00	0.1530d	0.0379b	14:30	20:30

Note: Distinct lowercase letters indicate significant differences between various mulching treatments under similar weather conditions at a significance level of 0.05 within the same experimental year.

The diurnal variation curves of jujube stem sap flow velocity in each treatment demonstrated a consistent pattern of "day high, night low" (Figures 5 and 6). Throughout the day, the sap flow velocity exhibited higher levels with significant fluctuations, which were strongly influenced by environmental factors, such as solar radiation, air temperature, and relative humidity. Conversely, during the night, the sap flow velocity remained relatively stable and at a lower level. Irrespective of weather conditions, there were no significant differences observed in stem sap flow velocity within the same treatment during the nighttime ($p > 0.05$). However, on sunny days, the stem sap flow velocity tended to be higher than that on cloudy days. The results from the variance analysis indicate significant variations in jujube stem sap flow velocity between sunny and cloudy days in both 2013 and 2014 ($p < 0.05$). In 2013, the sap flow velocity of the JBM + WCP, CC, and WCP treatments on sunny days showed an extremely significant difference from that on cloudy days ($p < 0.01$). Additionally, the sap flow velocity of the JBM treatment exhibited a significant difference ($p < 0.05$) between sunny and cloudy days. Similarly, in 2014, there were significant differences ($p < 0.01$) in sap flow velocities between sunny and cloudy days for the JBM + WCP and CC treatments. Additionally, the JBM treatment demonstrated a significant difference ($p < 0.05$) in sap flow velocities between sunny and cloudy days.

It is worth noting that under similar weather conditions, the stem sap flow velocities of each treatment did not significantly differ at night but did exhibit significant differences during the day (Figures 5 and 6). Throughout the two experimental years, the trend of sap flow velocity for the four treatments on sunny days followed the order JBM > CC >

JBM + WCP > WCP (Figure 5). A variance analysis was conducted on the four treatments under sunny and cloudy conditions to assess the impact of surface mulching measures on the jujube sap flow velocity. The resulting findings are presented in Table 3. The analysis revealed significant impacts of the surface mulching measures on sap flow velocities within the same experimental year (Table 3). Specifically, the sap flow velocities exhibited highly significant differences on sunny days ($p < 0.01$) and significant differences on cloudy days ($p < 0.05$). In July 2013, under cloudy weather conditions, there were no significant differences in the stem sap flow velocity between the JBM and CC treatments ($p > 0.05$), both of which demonstrated high velocities (Figure 6a and Table 3). The JBM + WCP treatment followed, while the WCP treatment exhibited the lowest velocity (Figure 6a). In July 2014, the stem sap flow velocity of the JBM treatment was significantly higher than that of other treatments on cloudy days ($p < 0.05$; Figure 6b and Table 3). There were no significant differences in the stem sap flow velocity between the JBM + WCP and CC treatments ($p > 0.05$; Table 3), while the WCP treatment generally exhibited a lower velocity (Figure 6b).

Table 3. The variance analysis results of sap flow velocities in tree trunks between different mulching treatments on sunny and cloudy days.

Year	Treatment	Sunny Days			Cloudy Days		
		WCP	JBM + WCP	CC	WCP	JBM + WCP	CC
2013	JBM	0.001 **	0.096	0.348	0.000 **	0.172	0.817
	WCP		0.104	0.019 *		0.007 **	0.000 **
	JBM + WCP			0.465			0.256
2014	JBM	0.000 **	0.076	0.324	0.003 **	0.020 *	0.023 *
	WCP		0.018*	0.002 **		0.478	0.447
	JBM + WCP			0.428			0.959

Note: ** indicates extremely significant differences in sap flow velocities between the two treatments at the 0.01 level, while * indicates significant differences at the 0.05 level.

3.2.2. Changes in Daily Average Sap Flow Velocity in Jujube Tree Trunks during the Growing Season

In order to analyze and compare the changes in jujube tree sap flow velocity throughout the entire growing season under different surface mulching measures, we plotted the daily average sap flow velocity of jujube tree trunks as a daily variation curve (Figure 7). This allowed us to visualize and study the fluctuations in the sap flow velocity on a daily basis.

The analysis in Figure 7 reveals distinctive monthly variation patterns in jujube sap flow velocity for all four treatments during the two growing seasons. The general trends of variation across the treatments were similar. In April, when rainfall was frequent and white clover was in the early growth phase, the transpiration water consumption was relatively low. Additionally, factors such as weak solar radiation, low air temperature, high air relative humidity, and limited soil evaporation capacity resulted in a higher soil moisture content. These favorable conditions promoted jujube tree transpiration, leading to higher sap flow velocity during this month. As May arrived, rainfall decreased and white clover entered the branching stage, requiring increased soil moisture. Meanwhile, solar radiation gradually intensified, air temperature rose, air relative humidity decreased, and soil evaporation increased significantly. These factors collectively resulted in decreased soil moisture content, adversely affecting jujube tree transpiration. Consequently, the sap flow velocity of jujube trees in all treatments was significantly lower than that in April. From June to mid-July, the rainfall frequency was low, but the amount of rainfall received was abundant. At this stage, the white clover entered the budding and flowering period, exhibiting vigorous growth with dense stems and leaves that effectively suppressed soil evaporation. This ensured a favorable soil water supply. Furthermore, jujube trees were primarily in the flowering and fruiting stage, characterized by the rapid growth of new shoots and lush branches, leading to strong transpiration. Consequently, the stem sap flow velocity increased significantly.

Between late July and mid-September, solar radiation reached its peak, accompanied by the highest temperatures and lowest relative humidity. This stage also witnessed maximum soil evaporation capacity. Although the white clover entered the pod formation–maturity stage, it still exhibited lush growth that contributed to increased transpiration. However, the limited rainfall during this period, coupled with the restricted soil moisture availability, failed to meet the demands of soil evaporation and plant transpiration. These factors, combined with meteorological influences, resulted in a fluctuating downward trend in the daily average jujube sap flow velocity. Subsequently, as the white clover entered the withering and yellowing period, the transpiration rates decreased significantly. The solar radiation intensity gradually decreased, temperatures started to drop, and there was a slight increase in relative humidity. These factors collectively contributed to a decrease in surface evaporation, and the soil entered a period of water storage. Although the transpiration water consumption of jujube trees slightly increased during this time, it is worth noting that the jujube trees had already entered the fruit ripening period. As a result, the leaves began to fall off, and the trees required only a small amount of water each day to sustain their physiological activities. Consequently, the sap flow velocity of the jujube tree trunks remained relatively low.

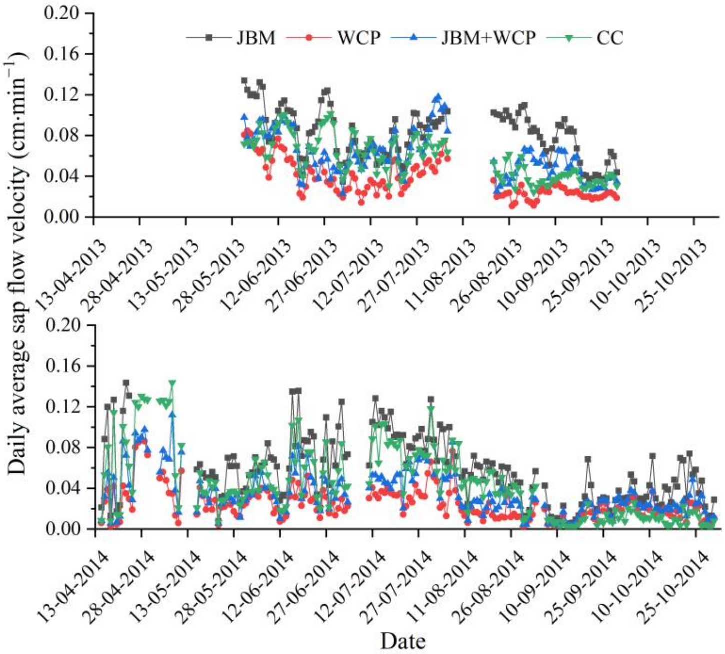

Figure 7. The daily average sap flow velocity changed under different mulching treatments during the growing season. The intermittent occurrence of sap flow velocity during certain periods in the graph was due to the malfunction of the sap flow sensors or data loggers during those time intervals, which resulted in inaccurate data collection. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

The statistical analysis of the monthly average jujube stem sap flow velocity from April to October is illustrated in Figure 8. Upon observation, it is evident that the overall sap flow velocity of the four treatments was higher in August 2013 (Figure 8a). The respective values were as follows: JBM (0.1005 cm·min^{-1}), JBM + WCP (0.0669 cm·min^{-1}), CC (0.0984 cm·min^{-1}), and WCP (0.0538 cm·min^{-1}) (Figure 8a). Similarly, in July 2014, the sap flow velocity reached its peak, with the following values: JBM (0.0946 cm·min^{-1}), JBM + WCP (0.0528 cm·min^{-1}), CC (0.0754 cm·min^{-1}), and WCP (0.0416 cm·min^{-1}) (Figure 8b). In October 2014, the monthly average jujube stem sap flow velocity for all four treatments reached its lowest point throughout the growing season (Figure 8b). Compared with July, the treatments showed decreases in sap flow velocity of 74.74% for JBM, 69.33% for JBM + WCP, 85.59% for CC, and 70.50% for WCP (Figure 8b). From April to August, the order of the monthly average stem sap flow velocity in the four treatments was as follows: JBM > CC > JBM + WCP > WCP (Figure 8a,b). From September to October, the order changed to JBM > JBM + WCP > WCP > CC (Figure 8a,b). A variance analysis of the monthly average jujube stem sap flow velocity was conducted for the four treatments. The results indicated that different surface mulching measures had a significant effect on the stem sap flow velocity ($p < 0.05$) in both experimental years (Figure 8a,b). Specifically, in 2013, there was an extremely significant difference between JBM and WCP ($p < 0.01$) (Figure 8a). In 2014, there was a significant difference between JBM and JBM + WCP ($p < 0.05$) and an extremely significant difference between JBM and WCP ($p < 0.01$) (Figure 8b).

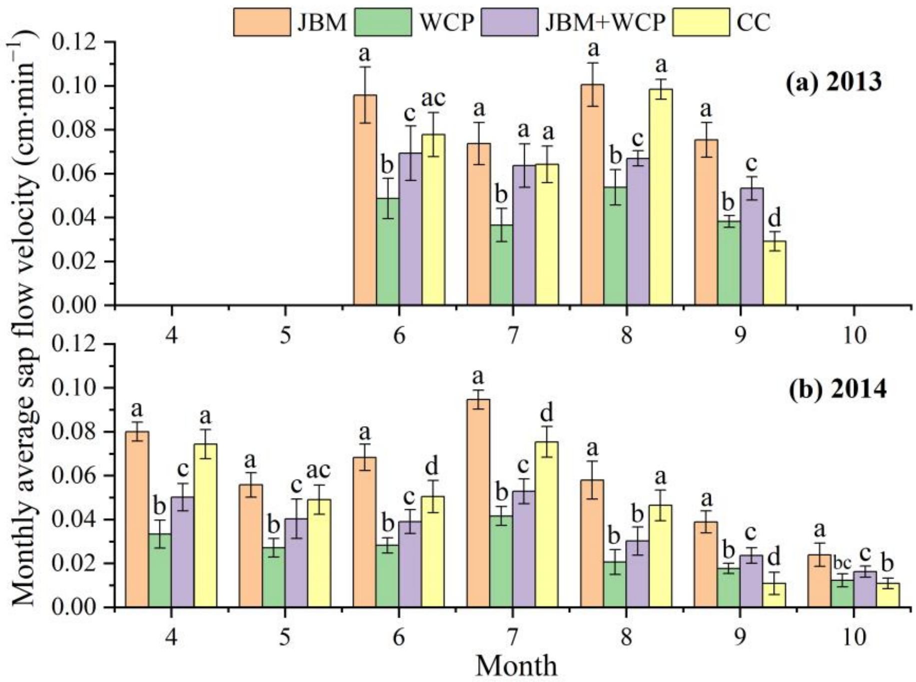

Figure 8. The variation in monthly average sap flow velocities of jujube tree trunks under different mulching treatments during the growing seasons of (**a**) 2013 and (**b**) 2014. Different lowercase letters in the same month indicate significant differences in sap flow velocities at the 0.05 significance level. The error bars represent the standard deviation. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

3.2.3. The Relationship between Stem Sap Flow and Environmental Factors

A Pearson correlation analysis was performed to assess the relationship between the daily average stem sap flow velocity (F_d) of the four treatments and five environmental factors (air temperature (T_{air}), vapor pressure deficit (VPD), wind speed (V_{wind}), photosynthetically active radiation (PAR), and average temperature of the 0–25 cm soil layer (T_{soil})) over two growing seasons of jujube trees (Table 4). To account for existing correlations between different environmental factors, we utilized a stepwise regression method to conduct a multiple linear stepwise regression analysis (Table 5). This analysis aimed to determine the relationship between the measured sap flow velocity and the aforementioned environmental factors. In this process, significance levels of 0.05 and 0.1 were employed as critical values for variable selection and removal, respectively. The tables below present the results of the correlation analysis and regression equations.

Table 4. Correlation analysis between sap flow velocities of jujube tree trunks and major environmental factors under different mulching treatments at different growth stages.

Year	Growth Stage	Treatment	T_{air}	VPD	V_{wind}	PAR	T_{soil}
2013	June to September	JBM	0.512 *	0.672 **	0.439 *	0.872 **	−0.2
		WCP	0.38	0.480 **	0.339	0.862 **	0.017
		JBM + WCP	0.415	0.316 **	0.39	0.779 **	0.108
		CC	0.643 **	0.744 **	0.658 **	0.911 **	0.001
2014	Sprouting and leaf spreading period	JBM	0.386	0.678 *	−0.267	0.808 **	0.446
		WCP	0.116	0.381	−0.16	0.801 **	0.066
		JBM + WCP	0.391	0.627 **	−0.097	0.909 **	0.355
		CC	0.473 *	0.707 **	−0.135	0.941 **	0.445 *
	Flowering and fruiting period	JBM	0.650 **	0.702 **	−0.005	0.690 **	0.671 **
		WCP	0.261 *	0.409 **	0.207	0.671 **	0.18
		JBM + WCP	0.362 **	0.479 **	0.115	0.689 **	0.319 *
		CC	0.580 **	0.676 **	0.122	0.696 **	0.581 **
	Fruit expansion period	JBM	0.828 **	0.816 **	0.705 **	0.697 **	0.848 **
		WCP	0.478 *	0.483 **	0.426 **	0.393 **	0.598 **
		JBM + WCP	0.618 **	0.656 **	0.599 **	0.485 **	0.738 **
		CC	0.701 **	0.680 **	0.644 **	0.571 **	0.769 **
	Fruit ripening period	JBM	−0.002	0.483 *	0.221	0.035	−0.044
		WCP	0.069	0.327	0.029	0.399 *	0.072
		JBM + WCP	0.245	0.337	0.009	0.426 *	0.244
		CC	0.227	0.155	−0.04	0.443 *	0.304

Note: * indicates a significant correlation between sap flow velocity and environmental factors at the 0.05 level, while ** indicates a highly significant correlation at the 0.01 level. The sap flow data from June to September 2013 were subjected to a comprehensive analysis, considering the limited amount of experimental data available. By contrast, the data collected in 2014 were analyzed by taking into account the distinct growth stages of the jujube trees.

Table 5. The regression equation of sap flow velocity of jujube tree trunks and major environmental factors under different mulching treatments at different growth stages.

Year	Growth Stage	Treatment	Regression Equation	R^2	*Sig.*
2013	June to September	JBM	$F_d = 3.597 \times 10^{-2} + 2.418 \times 10^{-2} VPD + 1.267 \times 10^{-3} PAR$	0.525	0.000
		WCP	$F_d = 8.885 \times 10^{-3} + 1.595 \times 10^{-3} PAR$	0.603	0.000
		JBM + WCP	$F_d = 3.016 \times 10^{-2} + 1.746 \times 10^{-3} PAR$	0.529	0.000
		CC	$F_d = 1.766 \times 10^{-2} + 2.453 \times 10^{-2} VPD + 8.970 \times 10^{-4} PAR$	0.607	0.000
2014	Sprouting and leaf spreading period	JBM	$F_d = -3.886 \times 10^{-1} + 2.861 \times 10^{-4} PAR + 2.792 \times 10^{-2} T_{soil}$	0.810	0.003
		WCP	$F_d = 7.632 \times 10^{-2} + 1.463 \times 10^{-4} PAR - 4.972 \times 10^{-3} T_{soil}$	0.730	0.000
		JBM + WCP	$F_d = 7.686 \times 10^{-3} + 1.652 \times 10^{-4} PAR$	0.827	0.000
		CC	$F_d = 1.065 \times 10^{-2} + 2.503 \times 10^{-4} PAR$	0.885	0.000
	Flowering and fruiting period	JBM	$F_d = -7.130 \times 10^{-2} + 1.023 \times 10^{-4} PAR + 4.001 \times 10^{-3} T_{soil}$	0.668	0.000
		WCP	$F_d = 7.312 \times 10^{-3} + 5.051 \times 10^{-5} PAR$	0.671	0.000
		JBM + WCP	$F_d = 8.890 \times 10^{-3} + 7.247 \times 10^{-5} PAR$	0.689	0.000
		CC	$F_d = -5.683 \times 10^{-2} + 9.830 \times 10^{-5} PAR + 2.782 \times 10^{-3} T_{soil}$	0.630	0.000
	Fruit expansion period	JBM	$F_d = -7.610 \times 10^{-2} + 5.206 \times 10^{-5} PAR + 4.306 \times 10^{-3} T_{soil}$	0.780	0.000
		WCP	$F_d = -2.097 \times 10^{-2} + 3.046 \times 10^{-5} PAR + 5.784 \times 10^{-3} T_{soil} - 5.080 \times 10^{-3} T_{air}$	0.496	0.000
		JBM + WCP	$F_d = -4.308 \times 10^{-2} + 3.887 \times 10^{-5} PAR + 7.749 \times 10^{-3} T_{soil} - 5.994 \times 10^{-3} T_{air}$	0.663	0.000
		CC	$F_d = 7.483 \times 10^{-2} + 4.450 \times 10^{-3} T_{soil}$	0.592	0.000
	Fruit ripening period	JBM	$F_d = 2.211 \times 10^{-2} + 9.066 \times 10^{-2} VPD - 7.274 \times 10^{-3} V_{wind} - 6.386 \times 10^{-5} PAR$	0.642	0.000
		WCP	$F_d = 1.391 \times 10^{-2} + 2.532 \times 10^{-5} PAR$	0.399	0.039
		JBM + WCP	$F_d = 1.335 \times 10^{-2} + 4.076 \times 10^{-2} VPD - 3.279 \times 10^{-3} V_{wind}$	0.572	0.000
		CC	$F_d = 6.887 \times 10^{-3} + 2.204 \times 10^{-5} PAR$	0.443	0.027

The tables provided demonstrate the relationships between jujube stem sap flow and various environmental factors under different surface mulching methods (Tables 4 and 5). For all four treatments, the sap flow velocity exhibited a positive correlation with five environmental factors: T_{air}, VPD, V_{wind}, PAR, and T_{soil} (Table 4). Among these factors, the correlation coefficient analysis revealed that PAR had the strongest association with the stem sap flow velocity for each treatment, displaying highly significant results ($p < 0.01$; Table 4). This suggests that regardless of the surface mulching method employed, PAR played a pivotal role as the primary driving factor influencing jujube transpiration. The high determination coefficients (R^2) of each regression equation indicated a good fit of the linear regression models (Table 5). Furthermore, the significance tests confirmed that the regression equations effectively captured the variation patterns of sap flow in relation to the main environmental factors (Table 5). Consequently, these regression equations successfully reveal the changing characteristics of sap flow in jujube trees in response to the primary environmental factors.

3.2.4. Monthly Variation of Jujube Tree Transpiration Water Consumption

The variations in monthly transpiration water consumption in jujube trees are illustrated in Figure 9. It is evident that over the course of two growing seasons, the transpiration water consumption of jujube trees under different surface mulching measures followed a consistent pattern characterized by an initial sharp increase and subsequent gradual decline (Figure 9a,b). In 2013, the highest transpiration water consumption for all treatments occurred in August (Figure 9a). The JBM treatment showed the highest value (25.84 mm), followed by CC (22.15 mm), JBM + WCP (20.15 mm), and WCP (19.66 mm) (Figure 9a). Conversely, the largest transpiration water consumption among treatments was observed in July 2014, with values of 40.89 mm for JBM, 31.78 mm for CC, 24.88 mm for JBM + WCP, and 19.61 mm for WCP (Figure 9b). Analyzing the total water consumption per plant for the four treatments during different periods, in the period from June to August 2013, the order of water consumption was as follows: JBM (73.42 mm) > CC (62.44 mm) > JBM + WCP (55.92 mm) > WCP (53.08 mm) (Figure 9a). From September to October, the order changed to JBM (41.87 mm) > JBM + WCP (27.62 mm) > WCP (27.60 mm) > CC (23.61 mm) (Figure 9a). In 2014, the total water consumption per plant for the jujube trees exhibited a consistent trend across all treatments. From April to August, the order was JBM (138.64 mm) > CC (110.08 mm) > JBM + WCP (83.59 mm) > WCP (64.07 mm) (Figure 9b). From September to October, the order changed to JBM (41.71 mm) > JBM + WCP (27.80 mm) > WCP (26.79 mm) > CC (17.61 mm) (Figure 9b). In summary, covering the entire soil surface of the jujube orchard with tree branches effectively promoted transpiration in the jujube trees. In the months of June to August 2013 and April to August 2014, both the JBM + WCP and WCP treatments exhibited lower water consumption per individual jujube tree than the CC treatment (Figure 9a,b). Specifically, in 2013, the JBM + WCP treatment showed a 10.45% reduction in water consumption compared with the CC treatment, while the WCP treatment displayed a 14.99% reduction (Figure 9a). Similarly, in 2014, the JBM + WCP treatment demonstrated a 24.07% reduction in water consumption compared with the CC treatment, with the WCP treatment showing an even larger reduction of 41.80% (Figure 9b). To assess the statistical significance, a one-way ANOVA was conducted on the monthly transpiration water consumption of jujube trees under different treatments. The analysis yielded the following results. In 2013, a significant difference ($p < 0.05$) was observed between the JBM treatment and both the JBM + WCP and CC treatments. Moreover, an extremely significant difference ($p < 0.01$) was found between the JBM treatment and the WCP treatment. In 2014, an extremely significant difference ($p < 0.01$) was observed between the JBM treatment and the WCP treatment. Additionally, a significant difference ($p < 0.05$) was found between the JBM treatment and the JBM + WCP treatment.

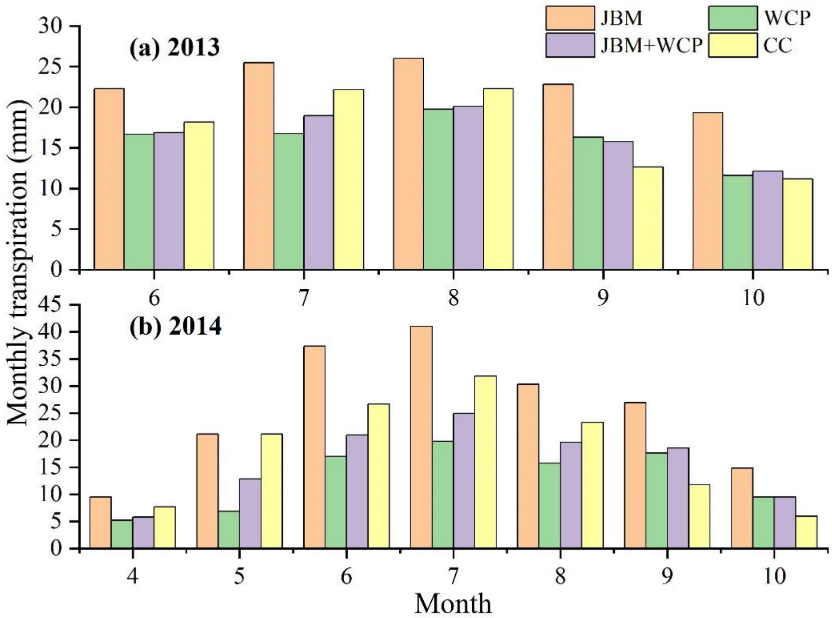

Figure 9. The variation of monthly transpiration in jujube trees under different mulching treatments during the growing seasons of (**a**) 2013 and (**b**) 2014. CC: clean cultivation; JBM: jujube branch mulching; WCP: white clover planting; JBM + WCP: jujube branch mulching with white clover planting.

4. Discussion

4.1. Impact of Grass Plantation and Tree Branch Mulching on Soil Moisture Conditions

Soil moisture is a vital environmental factor that profoundly impacts crop growth and development and serves as a primary limitation in rain-fed agricultural production [43]. The implementation of surface mulching, an efficient rain-fed agricultural technique, profoundly influences the soil moisture content by altering the movement and availability of soil moisture. This alteration is achieved through substantial modifications in the physical and chemical properties of both the land surface and the soil, ultimately affecting the type, availability, and movement of soil moisture. From an agronomic perspective, surface mulching has exhibited remarkable capabilities in reducing surface evaporation, mitigating surface runoff, minimizing soil erosion, and enhancing the utilization of natural precipitation in rain-fed agricultural areas [44,45].

This study revealed that out of the three surface mulching methods investigated, JBM (jujube branches covering the entire soil surface of the orchard) exhibited the highest water retention ability. Throughout the growth period of the jujube trees, the JBM treatment maintained a consistently high soil moisture content, significantly surpassing that of other treatments at all depths (0–65 cm) ($p < 0.05$; Figures 2–4). This finding aligns with the results of Ma et al.'s [46] study on the impact of mulching techniques on moisture rejuvenation in deep dry soils in loess hilly regions. Their conclusion also supports the notion that tree branch mulching can effectively enhance soil moisture storage and mitigate soil dryness. The strong water retention effect associated with tree branch mulching can be attributed to several factors. First, the layer of mulch derived from tree branches shields the soil surface from direct sunlight, thus reducing evaporation rates and preserving the soil moisture content. Additionally, the branches act as a cushion, dispersing the impact of raindrops and allowing for gradual infiltration into the soil, consequently minimizing direct water loss. Moreover, as the tree branches decompose, they release organic matter and nutrients that improve soil structure and texture through microbial activity, thereby enhancing the soil's water-holding capacity. Furthermore, tree branch mulching provides insulation that maintains a stable soil temperature, promoting soil moisture balance and reducing water evaporation. To summarize, tree branch mulching effectively reduces water evaporation and loss, improves soil structure, maintains soil temperature, and ultimately enhances water retention. An added advantage of tree branch mulching is that pruned branches serve as a renewable resource. Utilizing on-site branches as mulch allows for efficient resource utilization, minimizing waste without incurring additional energy or labor costs. Overall, on-site branch mulching plays a positive role in enhancing sustainable production capacity and environmental preservation in rain-fed orchards.

This research highlights the consistently low soil moisture content in the 0–65 cm soil layer, which was particularly notable during the critical water-demanding phase for the jujube trees when white clover planting (WCP) was implemented (Figure 2). Throughout 2013 and 2014, the soil moisture content was significantly lower for WCP by approximately 4.42% and 7.06% compared with that for the CC treatment ($p < 0.05$; Figure 2), signifying increased soil water consumption and the potential for competition for water resources between white clover and jujube trees. Similar observations have been documented in previous studies. Zhao et al. [47], utilizing stable isotope tracing methods, explored the water utilization strategies of fruit–herb compound systems across diverse habitats and seasons. Their findings indicated that introducing white clover into orchards during dry seasons elevates soil water consumption and potentially triggers water competition. Similarly, Bai et al. [48] noted a decline in soil moisture in the 0–120 cm soil layer subsequent to white clover planting in dryland orchards on the Loess Plateau, coupled with an increase in evaporation of 30.2 mm in comparison with clean-tilled orchards. This phenomenon can be attributed to several factors. (1) White clover, known for its short growth cycle, rapid growth rate, and robust root system, exhibits a substantial water absorption capacity. Consequently, the plant absorbs a considerable volume of soil water through its roots, intensifying soil water consumption in orchards. (2) The white clover leaves' large surface area and numerous stomata contribute to a high transpiration rate, thereby accelerating the loss of soil moisture and subsequently increasing overall soil water consumption in orchards. (3) Research indicates that the roots of white clover secrete organic substances, such as mucus, which can modify the physical properties and structure of the soil [49]. This alteration leads to increased porosity, facilitating quicker water flow and, consequently, a heightened risk of soil water loss. Hence, the cultivation of grass in dryland orchards necessitates a cautious approach. In regions with limited water availability, such as dryland agricultural areas, fruit trees rely on adequate water for growth and development. The introduction of grass competes with fruit trees for water and nutrient resources, resulting in compromised tree growth and diminished yields. In orchards equipped with irrigation facilities, particularly when introducing white clover, meticulous attention to orchard soil irrigation is paramount. This practice ensures that the water supply aligns with the plants' requirements, thereby preserving a balanced water state in the orchard.

4.2. Influence of Grass Planting and Tree Branch Mulching on Jujube Tree Transpiration

Transpiration, an essential physiological process for sustaining normal plant growth, plays a pivotal role in the upward transportation of mineral nutrients absorbed by roots from the soil and in regulating leaf temperature to avoid excessive exposure to sunlight. Extensive research has highlighted that over 90% of the sap flow within the trunk is allocated to plant transpiration [50]. The accurate measurement of sap flow in the trunk allows for the determination of water consumption attributable to plant transpiration. Surface mulching stands as a widely advocated agricultural technique in contemporary arid regions. Studies have illustrated that appropriately applied surface mulching can uphold a high transpiration rate in plants, substantially enhancing their overall transpiration [51].

The sap flow velocity of jujube trees and water consumption through transpiration in the JBM treatment consistently maintained high levels throughout the entire growth phase in comparison with that in the WCP treatment, showing remarkably significant differences ($p < 0.01$; Figures 7–9). This outcome underscores the efficacy of branch mulching in promoting transpiration in jujube trees. Notably, this finding aligns with Li's [52] research investigating the water dissipation mechanism of jujube trees in the loess hilly region, employing fish-scale pits and mulching techniques. Li's study revealed that covering jujube tree branches significantly amplified the sap flow velocity in the stems, reducing overall soil evaporation throughout the growth cycle while significantly augmenting transpiration during the fruiting and fruit enlargement stages. The potential reasons for this observation are multifaceted. (1) Branches act as a shield against soil moisture evaporation, creating a moisture-retaining layer that curtails soil moisture loss, thus ensuring an adequate water supply to jujube trees, consequently enhancing transpiration. (2) Branches serve to shield the soil surface, diminishing external environmental impacts on soil temperature and maintaining a relatively stable temperature. This stability in soil temperature is conducive to plant growth and root development, thereby supporting increased transpiration. (3) Branches aid in lowering soil temperature, reducing heat radiation on the soil surface and establishing an optimal temperature for plant growth. Cooler temperatures facilitate the absorption and movement of water in plant roots and soil, thereby fostering increased transpiration.

The investigation revealed that the sap flow velocity and transpiration of jujube trees under the WCP treatment remained consistently low, notably during the period from April to August, when these levels dipped below those observed under the CC treatment (Figures 8 and 9). This outcome contrasts with the findings posited by Xing [53] in his study on the impact of grass intercropping on the photosynthetic transpiration and water use efficiency of apple trees. Xing reported a 9.8% increase in the transpiration rate of apple leaves under white clover treatment compared with that under clean cultivation conditions. This could be explained by the irrigation practices utilized in the experiments. Xing's orchard was irrigated during the research, while our study was conducted solely under rain-fed conditions without any supplemental irrigation for the jujube orchard throughout the duration of the study. White clover, known for its high water requirement, poses a challenge in rain-fed orchards where water availability is restricted. When a substantial number of white clover plants coexist with fruit trees in an environment with inadequate water supply, they engage in competition for water resources, consequently limiting the transpiration of the fruit trees and impeding their normal growth. Therefore, the introduction of white clover in rain-fed orchards proves detrimental to the transpiration of fruit trees and can lead to insufficient water supply, subsequently affecting the healthy growth and yield of the fruit trees. To maintain the regular transpiration of fruit trees, measures need to be implemented to regulate the growth of white clover, such as employing regular pruning. This practice ensures that the root system of the fruit trees receives an adequate water supply.

5. Conclusions

Among the three surface cover measures, JBM demonstrated the highest water retention capability, effectively increasing the soil moisture content and maintaining a higher level of water content during the growth period of jujube trees. From April to August, the overall performance in terms of soil moisture content was ranked as follows: JBM > CC > JBM + WCP> WCP. From September to October, the ranking changed to JBM > JBM + WCP > WCP > CC. This suggests that the JBM treatment had the most significant impact on maintaining the jujube tree water content. Specifically, the soil moisture content under the JBM treatment was at its highest during the critical period of jujube tree water demand, measuring 17.23% in 2013 and 19.27% in 2014. In comparison, the WCP treatment led to a lower soil moisture content.

The sap flow velocity in jujube tree trunks was influenced by weather conditions. On sunny days, the sap flow velocity followed the order of JBM > CC > JBM + WCP > WCP, while under cloudy conditions, the sap flow velocity decreased across all treatments. Jujube tree transpiration water consumption was influenced by multiple factors, with photosynthetically active radiation being the primary factor. The highest transpiration water consumption occurred in August 2013 and July 2014. From June to August, the water consumption was ranked as follows: JBM > CC > JBM + WCP > WCP; from September to October, the ranking was JBM > JBM + WCP > WCP > CC.

In conclusion, the JBM treatment demonstrates excellent performance in terms of water retention capability, soil moisture content, and sap flow velocity. It positively impacts jujube tree growth and water utilization.

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