

Article

Effects of Deep Vertical Rotary Tillage on Soil Water Use and Yield Formation of Forage Maize on Semiarid Land

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Abstract: Forage maize is one of the most important feed crops for livestock production, and is mainly grown in northwest China. However, their growth is often stressed by limited soil water availability due to the arid climate. To provide more soil moisture, a high-efficiency tillage technique was required to make crops effectively use soil moisture in deep soil layers. Deep vertical rotary tillage is a promising choice for this purpose. In this study, a long-term (2020–2022) field experiment consisting of three treatments, i.e., traditional tillage (TT), deep rotary tillage (DT), and deep vertical rotary tillage (VRT), was carried out in semiarid areas of Loess Plateau, northwest China, to investigate the effects of VRT on soil water storage (SWS), phase crop evapotranspiration (ET_c) during the pre- and post-flowering periods, dry matter accumulation, grain yields and the water use efficiency (WUE) of forage maize. The results showed that VRT significantly improved the absorption of soil moisture from deep layers, especially in dry years. During the pre-flowering period of a dry year (2020), VRT decreased SWS by 7.6%–10.0% in the 60–180 cm layer, and by 17.6%–18.5% in the 180–300 cm layer, respectively, compared to DT and TT. As a result, VRT increased ET_c during the pre-flowering period by 6.1% and 9.2%, respectively. In wet years (2021 and 2022), VRT increased total ET_c by 2.0%–7.9% in 2021, and by 10.1%–14.9% in 2022, respectively. On average, VRT increased the dry matter weight per plant by 1.0%–7.8%, grain yields by 2.4%–38.6%, biomass yields by 3.4%–16.2%, and WUE by 10.1%–30.0%, respectively. Particularly, the benefit of VRT for increasing yields and WUE was more noticeable in dry years. It can be concluded that VRT is a drought-tolerant and yield-boosting tillage technique that is suitable for rain-fed forage maize in semiarid areas of Loess Plateau, northwest China.

Keywords: vertical rotary sub-soiling; plastic-film mulching; yield components; precipitation years; *Zea mays* L.



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1. Introduction

Spring maize (*Zea mays* L.) holds significant importance as one of the primary cereal crops cultivated in the semiarid regions of northwest China, particularly gaining prominence as the predominant crop in Gansu Province [1]. It plays a pivotal role in bolstering both provincial and national food security [2]. In northwest China, the total area of semiarid regions was 8.36×10^7 ha in 2023 [3], and the crop productivity of spring maize was estimated 7500–8500 kg ha^{−1} over the past decade [4]. In recent years, maize crop has become one of the dominant crops planted in China, with the planting area of 4.35×10^7 ha in 2023, accounting for 36% of total arable areas [5]. To adjust the planting structure, the Central Government has introduced several favorable policies aimed at reducing the prevailing crop cultivation areas since 2016, including replacing spring

maize with forage maize crops in northwest China [6]. Gansu Province has been singled out as a vital hub for forage maize production, designated as a pilot area for its advancement [7]. Notably, the reported planting area for forage maize in Gansu Province reached 2.5×10^5 ha in 2023, underscoring its burgeoning potential for the development of livestock production [8]. Besides, forage maize also had high nutritional value, high carbohydrate content, low lignin content, and high yield per unit area, which will make the crop one of the most important cultivated forage plants in China [9]. In the near future, forage maize in Gansu province will have huge development potential, and the planting areas will increasingly extend per planting structure adjustment policy [10]. However, drought events often occur during maize growth cycles, primarily due to the semiarid conditions prevalent in the Loess Plateau, characterized by limited water resources, sporadic rainfall, and the erratic distribution patterns of precipitation [11]. Maize is a C4 crop, characterized by its high water requirement of 450–550 mm per year, while forage maize showed an advantage in a lower water requirement of less than 400 mm due to its shorter growth period and smaller plant sizes [12]. Nevertheless, compounded by the predominance of small-scale farming, where tillage is often carried out using smaller machinery, forage maize productivity was often constrained by shallow tillage layers, compacted soil layers, and low nutrient uptake [13]. Prior research underscores the detrimental impact of traditional tillage practices on soil quality and crop development, exacerbating drought susceptibility and impeding yield stability and the growth of forage maize in northwest China [14,15].

Implementing appropriate tillage practices can significantly enhance water productivity [16]. In recent years, China has seen the development of an innovative tillage technique known as deep vertical rotary tillage, aimed at deepening tillage layers and breaking through plow pans [17]. Unlike traditional methods, this approach involves equipping plowing machinery with specialized soil tillage equipment, specifically the vertical deep rotary loosening cultivator [18]. The key part is a dedicated mechanical vertical spiral drill bit (Figure 1), capable of vertically penetrating soil layers up to 60 cm while rotating at high speeds (150 rps) to horizontally stir the soil, naturally forming ridges without disturbing the surrounding environment [19]. This process combines deep plowing, crushing, and ridge formation into a single operation [20]. Its primary advantage over traditional methods is its ability to deeply loosen the soil without disturbing its layers [10]. Following deep vertical rotary tillage, the arable layer becomes crushed, loosened, and granular, promoting improved ventilation, soil permeability, and water retention [21]. This technology revolutionizes dry land cultivation by adopting interval deep rotary tillage planting, creating a “U” shaped groove that effectively utilizes soil resources and natural precipitation below the tillage layer, expanding space for soil water storage and fertilizer retention [22]. By providing stable water and nutrients essential for crop growth and development, it enhances crop yields and quality, mitigates soil drought, prevents erosion, and fosters ecological improvements [23].

So far, this technology has been successfully implemented across more than ten crops in China, including *Dioscoreae opposita*, *Manihot esculenta*, *Saccharum officinarum*, and *Oryza sativa*, showing considerable potential for yield enhancement [24]. For instance, in Northeast China, maize yields treated with deep vertical rotary tillage have shown an increase of 10% to 30% compared to those under traditional tillage methods [25]. Similarly, in semiarid regions of the country, this tillage technique has resulted in significant maize yield improvements ranging from 24.8% to 156.8%, alongside notable enhancements in water use efficiency ranging from 18.9% to 92.3%, when compared to conventional methods [26]. Previous research attributes this yield increase to the optimized distribution of soil moisture and the augmented availability of soil water content [27]. While this innovative tillage approach has been successfully trialed in maize production areas across Northeast China, the North China Plain, and Southeast China, its application in dry-land forage maize cultivation in the semiarid locales of the Loess Plateau, northwest China, remains largely unexplored [28]. Hence, this study endeavors to address this technological gap within

Gansu province, China. Employing the “ridge-furrow with full plastic film mulching” technique as a foundation, three tillage methods were established, namely deep vertical rotary tillage, deep rotary tillage, and traditional tillage, respectively [29]. The underlying hypothesis of this study posits that deep vertical rotary tillage enhances the yields and water use efficiency by optimizing soil water storage, increasing soil moisture availability during pre- and post-flowering stages, and facilitating the accumulation of crop dry matter [30]. The objective of this study is to identify suitable tillage practices for full plastic film mulching on double ridges, and planting techniques for forage maize in semiarid regions of China, with the ultimate aim of furnishing a theoretical framework for enhancing yields and improving tillage efficiency in northwest China.

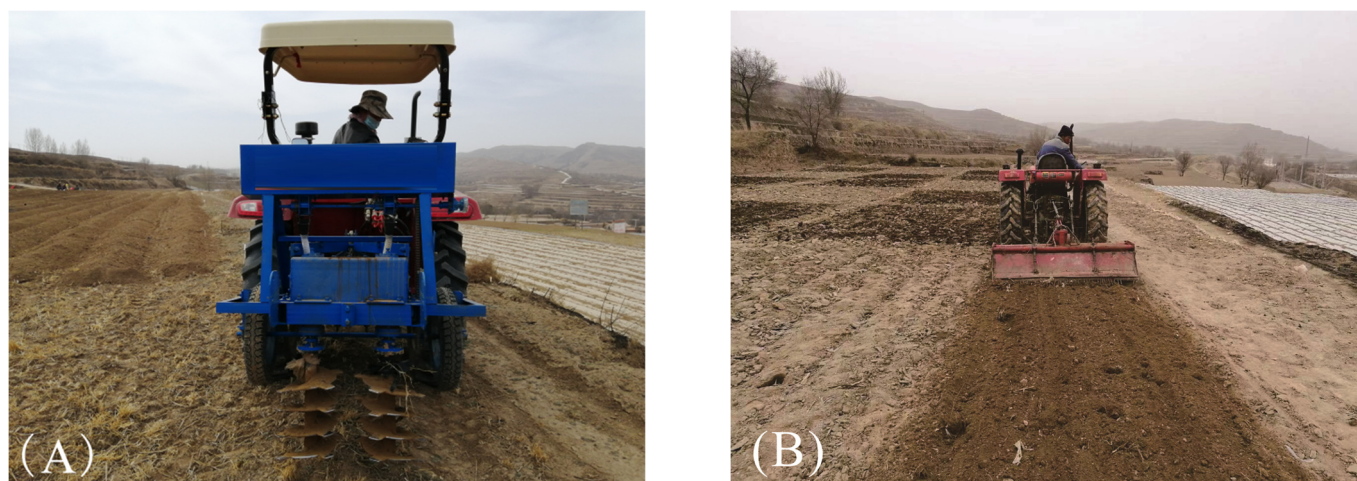


Figure 1. (A) The deep vertical rotary cultivator and (B) the traditional rotary tiller adopted in this experiment.

2. Materials and Methods

2.1. Site Description

The experimental site is situated at the Dingxi Experimental Station, affiliated with the Gansu Academy of Agricultural Sciences in the central region of the Loess Plateau, northwest China (104°36' E, 35°35' N; 1970 m above sea level) throughout the years 2020 to 2022 (Figure 2). The long-term (2010–2020) annual mean precipitation was 435 mm, of which 68% occurred from June to September; the mean annual air temperature was 6.2 °C; the total solar radiation was 5898 MJ m⁻²; the sunshine hours were 2500 h yr⁻¹; the effective accumulated temperature ≥ 10 °C was 2075.1 °C; and the frost-free period was 140 d. The prevailing weather exhibits characteristics of a continental temperate monsoon climate, with a precipitation-to-reference-evapotranspiration ratio (1318 mm) of 0.33, indicative of a typical semiarid climate. The cropping system implemented during the experimental years was an annual rotation of forage maize. The area belonged to the typical rain-fed agricultural area on arid lands. The relative variability of annual precipitation was 24%, with the insurance rate of precipitation ≥ 400 mm of 48%. The soil in the experimental area was a light loessial loam soil belonging to the family of lithological soils [31]. The texture was sandy loam, with an average bulk density of 1.25 g cm⁻³ in the 0–30 cm soil layers. The mean weight diameter and geometric mean diameter were 0.53 mm and 0.25 mm, respectively. The content of aggregates > 0.25 mm, and the percentage of aggregate disruption was 38.2%, and 36.3% in the 0–30 cm soil layers, respectively. The relative contents of soil water-stable aggregates were 3.92% for >2 mm aggregates, 40.18% for 2–0.25 mm aggregates, 36.73% for 0.25–0.053 mm aggregates, and 19.17% for <0.053 mm aggregates, showing the relatively good aggregate stability of the experimental soils. The field capacity was 21.2%, and the wilting point was 7.2%.

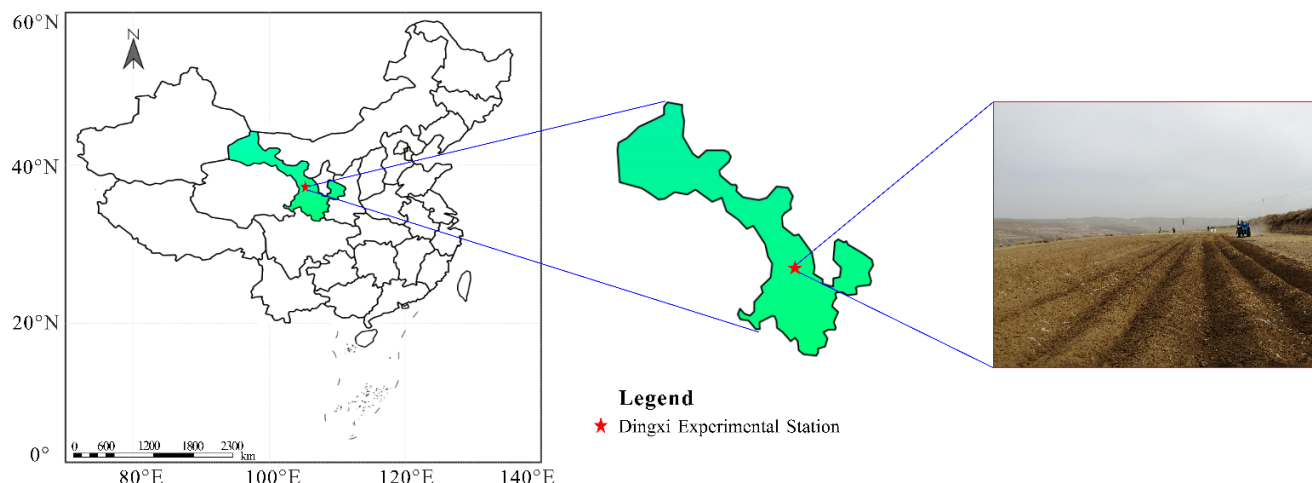


Figure 2. Schematic location of the Dingxi Experimental Station, Dingxi City, Gansu Province, China.

2.2. Experimental Design

The experimental treatments were assigned using a randomized block design, comprising traditional rotary tillage (TT, tillage depth 15 cm), deep rotary tillage (DT, tillage depth 25 cm), and deep vertical rotary tillage (VRT, tillage depth 40 cm). TT involved conventional small-scale rotary tillers, while DT utilized large deep rotary tillers. VRT, on the other hand, utilized a large deep vertical rotary tillage machine developed jointly by Dingxi Shanshi Agricultural Technology Group Company, Dingxi, China, and the Institute of Dry-land Agriculture of Gansu Academy of Agricultural Sciences. Chemical fertilizers, including urea, calcium superphosphate, and potassium chloride, were evenly broadcast before sowing, with application rates of 189 kg N ha^{-1} , $135 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$, and $120 \text{ kg K}_2\text{O ha}^{-1}$, respectively. Calcium superphosphate and potassium chloride served as base fertilizers, while for nitrogen fertilizer, 60% of the total nitrogen was broadcast as a base fertilizer, and the remaining 40% was top-dressed at the flowering stage of maize. All treatments were mulched with full plastic film. Forage maize seeds (*c.v.* Jinfengjie 607) were sown in furrows (4–5 cm deep) alternated with wide ridges (60 cm width, 10 cm height) and narrow ridges (40 cm width, 20 cm height). Each experimental plot covered an area of 40.6 m^2 (5.8 m wide, 7 m long), with 3 replicates per treatment. The planting density was set at $6.75 \times 10^4 \text{ plants ha}^{-1}$, with a plant-to-plant spacing of 29 cm. Forage maize was sown on 21 April and harvested on 13 October 2020; sown on April 20th and harvested on 8 October 2021; and sown on 22 April and harvested on 10 October 2022. No additional management practices were implemented, apart from weeding and fertilizing during the experiment.

2.3. Measurements

2.3.1. Precipitation and Air Temperature

Hourly records of precipitation and air temperature were obtained from an automatic meteorological station situated at the Dingxi Experimental Station of the Gansu Academy of Agricultural Sciences.

2.3.2. Dry Matter Accumulation

The dry matter (DM) weight of ten randomly selected uniform individual plants per plot was sampled at the seedling stage, jointing stage, and bell-mouth stage, while five plants were sampled at the flowering stage, filling stage, and harvesting stage. Only above-ground DM was measured. The plant samples were separated into grain, stems, leaves, sheathes, and cobs, then oven-dried at 105°C for 30 min to deactivate enzymes and respiratory activity. Subsequently, they were oven-dried at 80°C for a minimum of 72 h until reaching

a constant weight. The DM weight of each component was measured using an electronic balance and totaled to obtain the cumulative dry mass of the aforementioned components.

2.3.3. Soil Water Content

Soil water content (SWC, %) was determined using a 5 cm diameter auger at the seedling stage, flowering stage, and harvesting stage. Soil cores were extracted from both ridges and furrows to a depth of 0 to 300 cm at 20 cm intervals. The cores were oven-dried at 105 °C for 24 h until they reached a constant weight to calculate SWC. The SWC values from both ridge and furrow samples were averaged to represent the SWC of each plot.

2.3.4. Soil Water Storage

Soil water storage (SWS, mm) was calculated by multiplying the volumetric water content ($\text{cm}^3 \text{cm}^{-3}$) by the thickness of each soil layer down to a depth of 300 cm [32]. The calculation of SWS follows the equation below:

$$\text{SWS} = 10 \times h \times a \times \theta, \quad (1)$$

where h is soil depth (cm), a is soil bulk density (g cm^{-3}), and θ is soil water content by weight (%). Soil bulk density (g cm^{-3}) at each soil depth was determined using the stainless steel ring method [30].

2.3.5. Phase Crop Evapotranspiration (ET_c , mm)

Phase ET_c was estimated using a water balance equation based on the number of growing days within each growth stage [33]. This calculation involved subtracting the soil water storage (SWS) at the beginning of a growth stage from the SWS at the end of the same stage, and adding the precipitation received during the growth stages. During the experimental years, phase precipitation remained below 40 mm, while ET_c reached levels of up to 80 mm, thus disregarding deep percolation. Given the flat surface of the plots and their separation by ridges, surface runoff was deemed negligible. Consequently, phase ET_c was determined using the following equation:

$$\text{Phase } \text{ET}_c = \text{SWS}_{\text{start}} - \text{SWS}_{\text{end}} + \text{Pre}, \quad (2)$$

where $\text{SWS}_{\text{start}}$ and SWS_{end} are soil water storage (mm) in the 0–300 cm soil layer at the start and the end of each growth stage, respectively. Pre is phase precipitation (mm) during the growing stages.

2.3.6. Crop Water Consumption (ET , mm)

In this study, crop water consumption was equal to total crop evapotranspiration (ET , mm). It was a sum of different phase ET_c during the whole growth period. Therefore, ET was determined using the following equation:

$$\text{ET} = \sum_{i=1}^n \text{phase } \text{ET}_c \quad (3)$$

where ET is crop water consumption (mm) in the 0–300 cm soil layer during the entire growth period. $\text{Phase } \text{ET}_c$ is crop evapotranspiration (mm) within each growth stage, and n is the number of growth stages.

2.3.7. Grain Yield and Yield Components

At maize maturity, ten uniform plants were randomly selected from each plot to investigate various yield components, including stem diameter, plant height, ear length, ear diameter, bald length, kernel number per ear, 100-kernel weight, and double ear rate. To determine grain yields, ears were manually harvested from 20 randomly chosen maize plants in each plot. Following harvest, maize husks were removed, and cobs were air-dried for a minimum of three weeks until they reached a constant mass. Subsequently, the grains

were separated, cleaned, and weighed, with grain yields calculated based on dry weight (14% moisture content, w/w).

2.3.8. Water Use Efficiency

Water use efficiency (WUE, $\text{kg ha}^{-1} \text{ mm}^{-1}$) was calculated as the grain yield (kg ha^{-1}) produced per unit of crop evapotranspiration (mm) [34]. The following formula was used for WUE calculation:

$$WUE = GY/ET, \quad (4)$$

where GY represents maize grain yield or biomass yield (kg ha^{-1}) and ET represents crop water consumption (mm) during the entire growing season in each year.

2.4. Statistical Analysis

Prior to conducting statistical analysis, the normality of the data and homogeneity of variances were assessed. Significant differences among the treatments in soil water content (SWC), soil water storage (SWS), dry matter (DM), phase evapotranspiration (ET_c), grain yield (GY), and water use efficiency (WUE) were examined using analysis of variance (ANOVA), performed with SPSS 19.0 software (SPSS Institute Inc., Chicago, IL, USA). Treatment effects were evaluated using Duncan's multiple-range test ($p < 0.05$).

3. Results

3.1. Precipitation and Air Temperature during 2020 to 2022

From 2000 to 2020, the total seasonal precipitation during the growth period of forage maize amounted to 380.5 mm, with a mean air temperature of 15.6 °C. Specifically, the average temperature during the growth period of 2020 was 15.8 °C, with precipitation totaling 340.7 mm, marking a decrease of 10.5% compared to the long-term annual average (Figure 3). Similarly, the average temperatures for the 2021 and 2022 growth seasons were 15.3 °C and 15.4 °C, respectively, with precipitation levels reaching 442.9 mm and 436.8 mm, representing increases of 16.4% and 14.8%, respectively. An analysis of the precipitation data categorized the 2020 season as relatively dry, given the 10% decrease in precipitation, which can lead to significant drought in a semiarid climate. Moreover, the average temperature during the bell-mouth to flowering period in 2020 was 20.4 °C, with the high temperature and drought adversely affecting the flowering and pollination of forage maize plants, resulting in a significant reduction in grain yields. In contrast, the 2021 and 2022 seasons were both considered wet years, with air temperature and precipitation conditions favorably conducive to maize growth, ultimately contributing to high yield formation.

3.2. Effect of Deep Vertical Rotary Tillage on Soil Water Storage

In the dry year of 2020, the flowering stage of forage maize was adversely affected by reduced precipitation (150.8 mm) during the pre-flowering period. Comparatively, soil water storage (SWS) in the 0–80 cm soil layer decreased significantly, by 32.4%, compared to levels prior to sowing (Figure 4). Both deep vertical rotary tillage (VRT) and deep rotary tillage (DT) exhibited a reduction in SWS in the 0–40 cm soil layer, by 4.2 mm, compared to traditional tillage (TT). However, VRT demonstrated a more pronounced decrease in deeper SWS levels. For instance, VRT resulted in a SWS of 121.8 mm in the 180–300 cm soil layers, or a significant reduction by 20.5 mm and 25.3 mm over the three years, compared to DT and TT, respectively. At harvest, no significant difference in SWS was observed in the 0–180 cm soil layer, while VRT exhibited a decrease in SWS in the 180–300 cm layer by 21.3 mm and 11.6 mm compared to DT and TT, respectively. In the wet years of 2021 and 2022, VRT displayed lower SWS levels in the 0–80 cm soil layer at sowing compared to DT and TT, with a decrease ranging from 18.2 mm to 21.5 mm. At the flowering stage, both VRT and DT resulted in decreased SWS in the 0–80 cm soil layer, which was 154.4 mm and 151.5 mm averaged over 2021 and 2022, with reductions ranging from 6.3 mm to 7.5 mm compared to TT. Additionally, in the 80–240 cm soil layers, SWS with

VRT and DT decreased by 59.1 mm and 20.1 mm, respectively, compared to TT, indicating more substantial differences in SWS in deeper soil layers. At harvest, VRT brought out significantly lower SWS in the 0–80 cm soil layer than the DT and TT treatments did, with a decrease ranging from 10.6 mm to 20.4 mm. Similarly, the SWS of VRT was 7.9 mm to 14.9 mm lower in the 100–140 cm layer and 17.1 mm to 31.5 mm lower in the 140–300 cm layer compared to DT and TT, respectively.

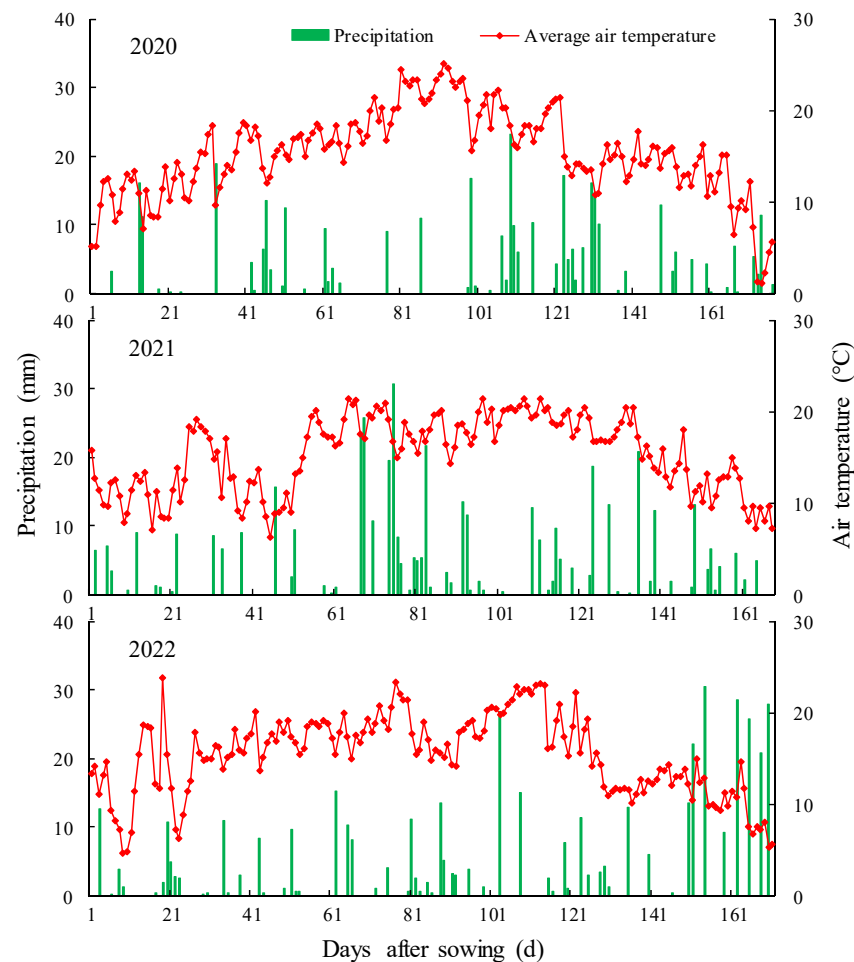


Figure 3. Dynamic of precipitation and average air temperature during the growth stages of forage maize from 2020 to 2022.

3.3. Effect of Deep Vertical Rotary Tillage on Crop Water Consumption

It was observed that VRT had a significant impact on crop water consumption (ET_c , mm) within the 0–300 cm soil layer (Figure 5). Taking the pre- and post-flowering periods of forage maize as examples, in the dry year of 2020, VRT had an ET_c of 193.6 mm during pre-flowering period, or an increase by 13.9 mm to 20.3 mm compared to DT and TT ($p < 0.05$). There were no significant differences in ET_c during the post-flowering period among treatments. However, VRT increased the total ET_c (392.4 mm) by 11.2 mm to 15.1 mm compared to DT and TT ($p < 0.05$). In the wet years of 2021 and 2022, VRT increased ET_c during the pre-flowering period by 88.1 mm compared to DT ($p < 0.05$), while the increase compared to TT was only 8.1 mm ($p > 0.05$). Regarding ET_c during the post-flowering period, it decreased by 98.9 mm and 22.4 mm compared to DT and TT, respectively ($p < 0.05$). Consequently, the total crop water consumption of VRT was 482.8 mm during the entire growing period over the three years, or a decrease by 10.8 mm and 30.5 mm, respectively, compared to DT and TT. It was found that VRT exerted a significant impact on crop water consumption in the 0–300 cm soil layer.

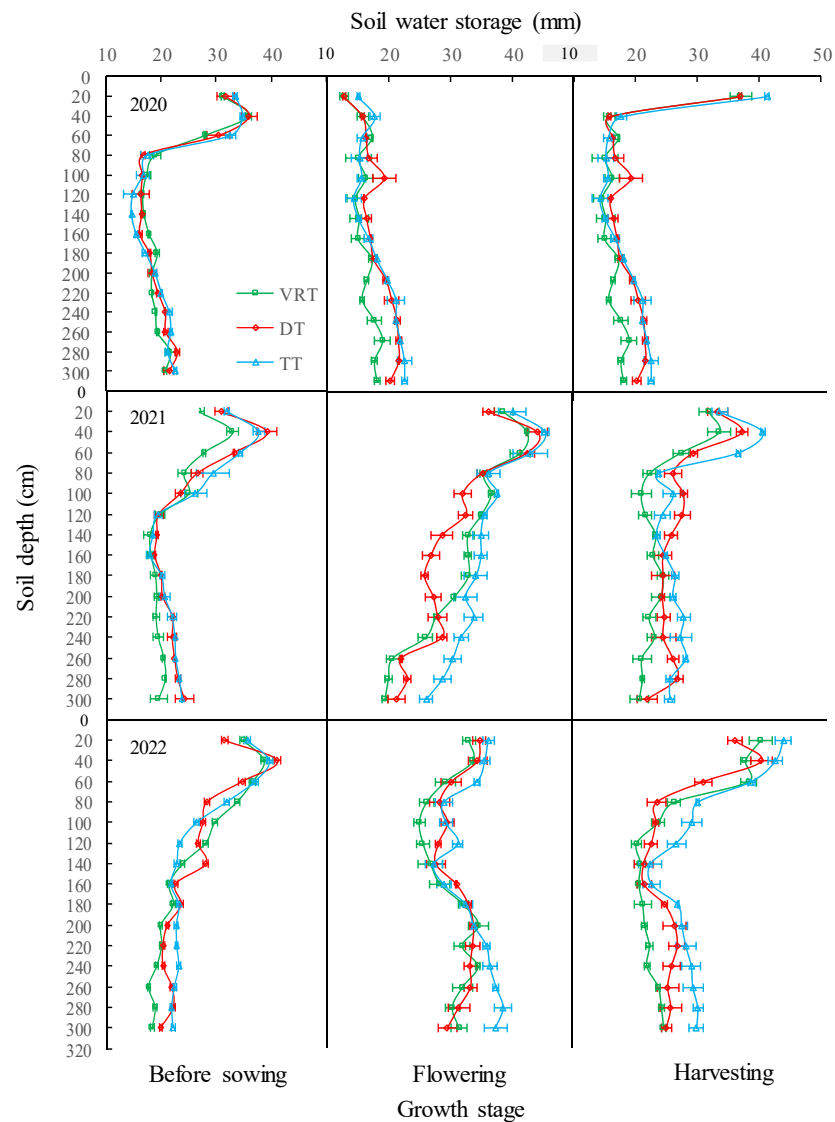


Figure 4. Dynamics of soil water storage (SWS, mm) in 0–300 cm soil depth at the key growth stages of forage maize. Bars stand for standard errors (SE).

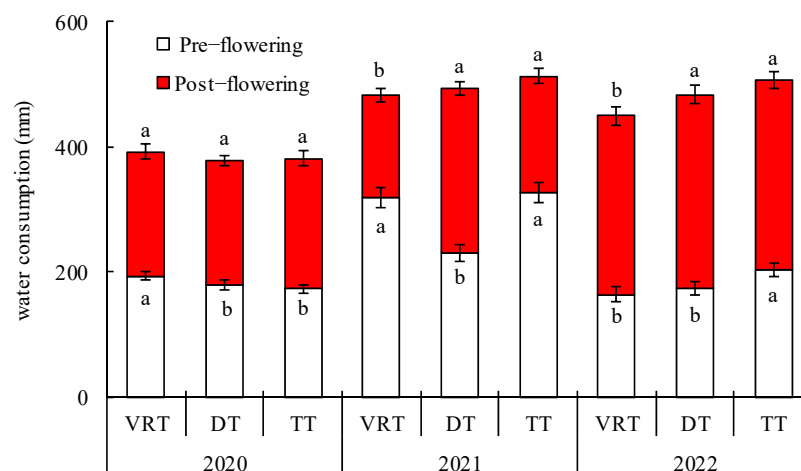


Figure 5. Dynamics of crop water consumption in 0–300 cm soil layers of forage maize during the pre- and post-flowering periods. Different letters in each year of the sub-figures indicate significant differences at $p < 0.05$. Bars stand for standard errors (SE).

3.4. Effect of Deep Vertical Rotary Tillage on Dry Matter Accumulation

Deep vertical rotary tillage had a significant impact on the dry matter weight accumulation of forage maize (Table 1). Over the consecutive experimental years, VRT consistently yielded significantly higher dry matter weights at the flowering ($186.8 \text{ g plant}^{-1}$), filling ($388.8 \text{ g plant}^{-1}$), and harvest ($518.1 \text{ g plant}^{-1}$) stages of forage maize compared to DT and TT, respectively ($p < 0.05$). Conversely, no significant difference was observed between DT and TT across the three years. Similarly, there were no significant differences among treatments at the seedling and jointing stages. In more detail, during the dry year of 2020, dry matter accumulation with VRT was 182.8 , 291.7 , and $424.6 \text{ g plant}^{-1}$ at the flowering, filling, and harvest stages, or 14.1% to 18.3% , 9.7% to 15.1% , and 10.2% to 14.7% higher, respectively, compared to DT and TT. Likewise, the increase in dry matter accumulation with VRT was 22.9% to 29.1% , 15.9% to 17.9% , and 10.6% to 12.0% in 2021, and 12.8% to 14.5% , 6.4% to 8.4% , and 9.7% to 12.4% in 2022, compared to DT and TT, respectively. These results indicate that deep vertical rotary tillage significantly promotes the dry matter accumulation of forage maize regardless of precipitation levels.

Table 1. Effects of different tillage treatments on above-ground dry matter accumulation of forage maize (g plant^{-1}).

Year	Treatments	Seedling	Jointing	Flowering	Filling	Harvest
2020	VRT	$16.9 \pm 1.3 \text{ a}$	$83.0 \pm 5.1 \text{ a}$	$182.8 \pm 10.5 \text{ a}$	$291.7 \pm 27.5 \text{ a}$	$424.6 \pm 31.6 \text{ a}$
	DT	$16.2 \pm 1.1 \text{ a}$	$77.5 \pm 4.9 \text{ b}$	$166.6 \pm 9.5 \text{ b}$	$264.7 \pm 22.4 \text{ b}$	$401.9 \pm 27.5 \text{ b}$
	TT	$16.2 \pm 0.8 \text{ a}$	$77.2 \pm 4.5 \text{ b}$	$158.9 \pm 8.9 \text{ b}$	$254.2 \pm 20.8 \text{ b}$	$393.8 \pm 24.3 \text{ b}$
2021	VRT	$30.1 \pm 1.9 \text{ a}$	$88.6 \pm 3.2 \text{ a}$	$193.4 \pm 12.6 \text{ a}$	$464.1 \pm 42.5 \text{ a}$	$567.2 \pm 57.5 \text{ a}$
	DT	$29.7 \pm 1.6 \text{ a}$	$85.5 \pm 3.4 \text{ a}$	$166.9 \pm 10.3 \text{ b}$	$419.7 \pm 40.6 \text{ b}$	$512.7 \pm 46.1 \text{ b}$
	TT	$29.7 \pm 1.7 \text{ a}$	$85.4 \pm 3.1 \text{ a}$	$164.0 \pm 10.2 \text{ b}$	$414.4 \pm 35.0 \text{ b}$	$502.9 \pm 40.9 \text{ b}$
2022	VRT	$28.3 \pm 1.1 \text{ a}$	$92.1 \pm 4.6 \text{ a}$	$184.2 \pm 8.9 \text{ a}$	$410.8 \pm 38.6 \text{ a}$	$562.5 \pm 36.9 \text{ a}$
	DT	$26.6 \pm 0.8 \text{ b}$	$90.2 \pm 4.5 \text{ a}$	$173.1 \pm 8.6 \text{ b}$	$374.4 \pm 32.4 \text{ b}$	$528.4 \pm 34.2 \text{ b}$
	TT	$25.4 \pm 0.8 \text{ b}$	$89.4 \pm 4.4 \text{ a}$	$170.0 \pm 8.2 \text{ b}$	$365.5 \pm 30.7 \text{ b}$	$522.0 \pm 32.9 \text{ b}$

Note: Different letters in each year of columns represent significant differences at $p < 0.05$.

3.5. Effect of Deep Vertical Rotary Tillage on Yield Components

Deep vertical rotary tillage was beneficial for the formation of yield components in forage maize (Table 2). Stem diameters treated with VRT and DT were 3.3 cm and 3.5 cm in 2020 and 2022, or an increase by 7.4% and 8.3% ($p < 0.05$) compared to TT, respectively. Notably, VRT generated a significant elongation of ear length of 14.9 cm and 24.0 cm in 2020 and 2022, compared to DT and TT in 2020 and 2021 ($p < 0.05$), resulting in an increase of 1.8% to 7.3% over the three years. However, the effect of different tillage treatments on ear diameter and the 100-kernel weight of forage maize was not significant during the three consecutive years. Nevertheless, there were significant differences in bald length, kernel number per ear, and double ear rate ($p < 0.05$). For instance, VRT had an average bald length of 3.9 cm over the three years, or a decrease by 11.3% to 38.1% compared to DT and TT, respectively, over the three years, while the kernel number per ear was 426.0 with VRT, or an increase by 8.1% to 13.2% in 2020 and 2021. Regarding double ear rate, there was a significant interaction between year and tillage treatments. No double ears were observed in the dry year of 2020. However, in the wet years of 2021 and 2022, the double ear rate with VRT increased by 42.8% to 51.5% in 2021 and 27.9% to 32.3% in 2022, compared to DT and TT, respectively.

Table 2. Effects of different tillage treatments on yield components of forage maize.

Year	Treatments	Stem Diameter (cm)	Ear Length (cm)	Ear Diameter (mm)	Bald Length (cm)	Kernel Number per Ear (kernel)	100-Kernel Weight (g)	Double Ear Rate (%)
2020	VRT	3.3 ± 0.2 a	14.9 ± 1.6 a	31.5 ± 3.6 a	6.4 ± 0.8 b	163.5 ± 14.2 a	22.7 ± 2.3 a	0.0 ± 0.0 a
	DT	3.2 ± 0.2 a	14.0 ± 1.4 b	31.3 ± 3.5 a	7.4 ± 0.9 a	144.5 ± 13.9 b	22.4 ± 2.0 a	0.0 ± 0.0 a
	TT	3.1 ± 0.2 b	13.9 ± 1.2 b	31.1 ± 3.5 a	7.2 ± 0.9 a	134.5 ± 11.8 b	22.2 ± 2.0 a	0.0 ± 0.0 a
2021	VRT	3.3 ± 0.2 a	24.0 ± 2.0 a	53.0 ± 6.8 a	1.6 ± 0.1 c	541.2 ± 45.6 a	42.5 ± 3.8 a	34.7 ± 3.6 a
	DT	3.2 ± 0.2 a	22.9 ± 1.9 b	51.7 ± 6.5 a	2.1 ± 0.2 b	500.8 ± 42.3 b	41.2 ± 3.7 a	24.3 ± 1.9 b
	TT	3.2 ± 0.2 a	22.8 ± 1.9 b	51.4 ± 6.4 a	2.6 ± 0.2 a	492.9 ± 41.0 b	40.7 ± 3.5 a	22.9 ± 1.7 c
2022	VRT	3.5 ± 0.4 a	24.3 ± 2.1 a	55.0 ± 6.9 a	3.8 ± 0.3 b	573.4 ± 66.3 a	41.9 ± 3.4 a	63.8 ± 5.5 a
	DT	3.4 ± 0.3 a	23.9 ± 2.0 a	54.5 ± 6.6 a	4.7 ± 0.4 a	550.4 ± 60.2 a	41.5 ± 3.1 a	49.9 ± 4.3 b
	TT	3.2 ± 0.2 b	23.4 ± 2.0 a	54.2 ± 6.6 a	4.8 ± 0.5 a	549.0 ± 57.6 a	41.2 ± 3.1 a	48.2 ± 4.2 b

Note: Different letters in each year of columns represent significant differences at $p < 0.05$.

3.6. Effects of Deep Vertical Rotary Tillage on Grain Yield, Biomass Yield and WUE

Deep vertical rotary tillage significantly impacted the grain yield, biomass yield, and water use efficiency (WUE) of forage maize (Figure 6). Over the three years, VRT generated the greatest grain yields of 5226.7 kg ha^{−1} in 2020, 10,100.9 kg ha^{−1} in 2021, and 10,738.4 kg ha^{−1} in 2022, or an increase by 21.0% to 32.4% (2020), 7.7% to 11.1% (2021), and 13.8% to 15.4% (2022), respectively, compared to DT and TT ($p < 0.05$). However, significant differences in grain yields were only observed between DT and TT in the dry year of 2020 ($p < 0.05$); no significant difference was found in 2021 and 2022 ($p > 0.05$). The trend of biomass yields was similar to that of grain yields, with an average biomass yield of 34,275.8 kg ha^{−1} in the three years. Specifically, biomass yields with VRT increased by 12.2% to 12.4%, 15.3% to 21.4%, and 6.7% to 14.9% over the three years compared to DT and TT, respectively, while the difference in biomass yields between DT and TT was not significant ($p > 0.05$).

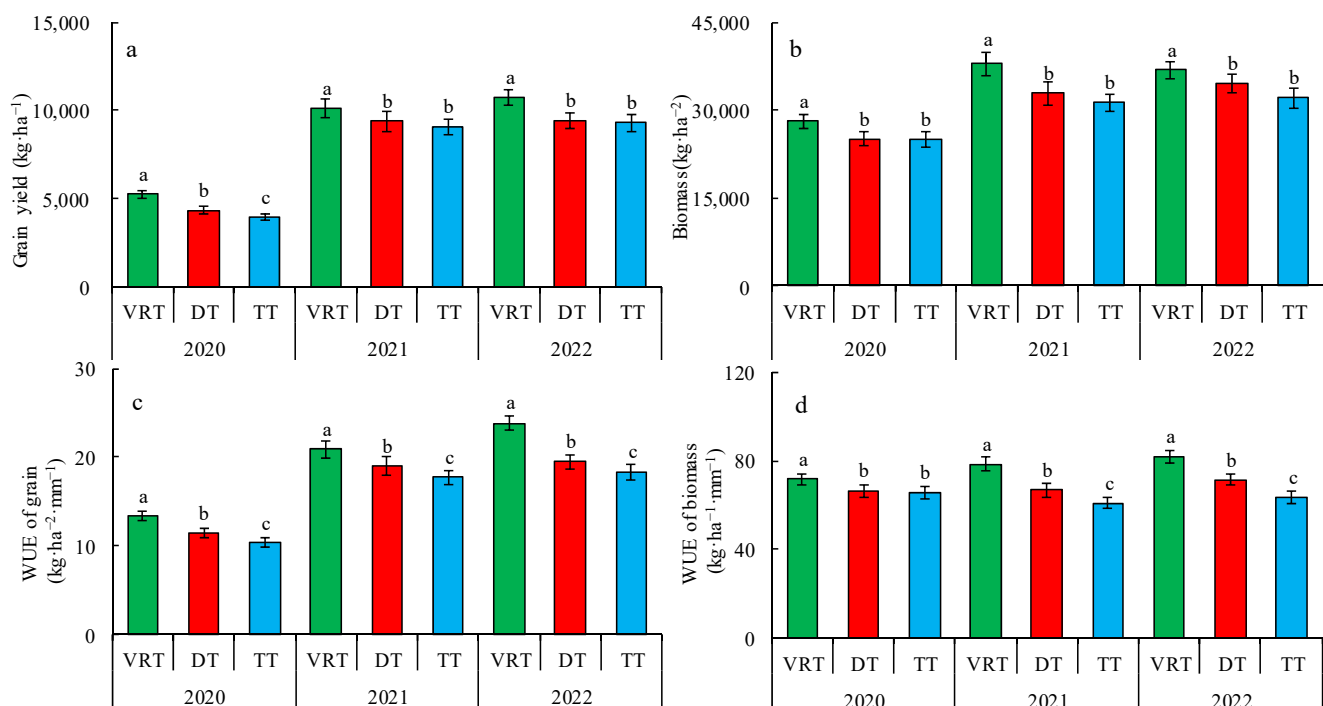


Figure 6. The (a) grain yield, (b) biomass yield, (c) water use efficiency based on grain yield, and (d) water use efficiency based on biomass yield of forage maize. Note: different letters in each year of the sub-figures indicate significant differences at $p < 0.05$. Bars stand for standard errors (SE).

In this study, WUE was calculated based on both grain yields and biomass yields. Over the three consecutive experimental years, VRT gained WUE based on grain yields of $19.7 \text{ kg ha}^{-1} \text{ mm}^{-1}$, or an increase by 16.4% to 28.7%, 10.1% to 18.1%, and 22.4% to 30.0% compared to DT and TT, respectively ($p < 0.05$). Unlike the grain and biomass yields, the WUE of DT was $16.4 \text{ kg ha}^{-1} \text{ mm}^{-1}$ over the three years. This value was significantly higher than that of TT, with an average increase by 8.3% from 2020 to 2022. The performance of WUE based on biomass yields closely paralleled that of WUE based on grain yields. For instance, the WUE of biomass yields was 71.6 to $81.8 \text{ kg ha}^{-1} \text{ mm}^{-1}$ with VRT, or an increase by 7.8% to 29.4% compared to DT and TT, respectively ($p < 0.05$) from 2020 to 2022. Additionally, the WUE of biomass yields treated with DT was 7.2% to 8.9% higher than that of TT in 2021 and 2022 ($p < 0.05$).

3.7. Correlation Analysis

In this study, dry matter accumulation, ear length, ear diameter, kernel number per ear, 100-kernel weight, and double ear rate all had an extremely significant positive correlation with grain yield, biomass yield, and WUE based on grain yield ($p < 0.01$) (Table 3). Bald length had an extremely significant negative correlation with grain yield, biomass yield, and WUE based on grain yield ($p < 0.01$). SWS and ET_c showed significant correlations with grain yield and WUE based on grain yield ($p < 0.05$). Most factors did not have significant correlation with WUE based on biomass yield, except stem diameter. The results implied that deep vertical rotary tillage significantly increased grain yield and WUE mainly through the increase of dry matter weight, ear length, kernel number per ear, and double ear rate, and the decrease of bald length during the three experimental years.

Table 3. Correlation analysis among grain yield, biomass yield, WUE, and soil water storage, crop water consumption, dry matter accumulation, and yield components of forage maize.

Correlation Coefficient (R)	SWS	ET_c	DM	SD	EL	ED	BL	KN	KW	DER
Grain yield	0.73 *	0.87 **	0.99 **	0.57	0.99 **	0.98 **	−0.86 **	0.99 **	0.98 **	0.89 **
Biomass yield	0.61	0.72 *	0.98 **	0.68 *	0.92 **	0.89 **	−0.82 **	0.91 **	0.90 **	0.85 **
WUE based on grain yield	0.64 *	0.74 *	0.98 **	0.71 *	0.94 **	0.93 **	−0.80 **	0.94 **	0.92 **	0.91 **
WUE based on biomass yield	−0.05	−0.09	0.48	0.81 **	0.29	0.24	−0.24	0.28	0.23	0.46

Note: * and ** represent significant correlations at $p < 0.05$ and $p < 0.01$. SWS, soil water storage; ET_c , crop water consumption; DM, dry matter accumulation; SD, stem diameter; EL, ear length; ED, ear diameter; BL, bald length; KN, kernel number per ear; KW, 100-kernel weight; DER, double ear rate.

4. Discussion

The adoption of sustainable farming practices plays a vital role in enhancing soil moisture conditions within the tillage layer, thereby fostering an optimal soil environment for crop development [35]. Over the past decade, the widespread implementation of ridge-furrow with full plastic film mulching technology has notably boosted maize production in the rain-fed semiarid regions of the Loess Plateau in northwest China [36]. However, this advancement has also led to heightened soil moisture consumption, resulting in water resource deficits [37]. Furthermore, conventional tillage methods such as plowing and rotary tillage, prevalent in the Loess Plateau, have caused soil compaction, shallower plowing layers, increased soil bulk density, reduced permeability, and a diminished water retention capacity [38]. These factors collectively impeded the efficient utilization of available soil water by crop root systems [39].

Research has demonstrated that deep vertical rotary tillage technology substantially enhanced effective soil water storage for sugarcane (*Saccharum* spp.) in southern China [40]. During dry years, this technology increased soil water storage (SWS) by 81.8% to 136.9% in the 0–200 cm soil layer, and by 34.3% to 86.9% during normal years, indicating its

significant drought resistance [41]. In the dry year of 2020, SWS in the 0–40 cm layer with VRT was 14.8% lower compared to TT, and 7.9% lower in the 60–180 cm layer compared to DT and TT during the pre-flowering period of forage maize. A similar result was also found in plastic film mulched spring maize on the semiarid Loess Plateau of China [28]. However, during the post-flowering period, SWS treated with VRT was 2.8% higher in the 0–80 cm layer than DT, but 12.2% lower than TT. This discrepancy may be attributed to variations in water uptake ability among the three tillage treatments, with VRT potentially enhancing the crop root absorption of the soil moisture in deeper layers [42]. Consequently, crop water consumption (ET_c) with VRT was 7.7% and 11.7% higher in the 0–300 cm layer during the pre-flowering period of 2020, compared to DT and TT. In northern China, deep vertical tillage technology also showed great potential in increasing the soil water conservation ability compared to conventional tillage practices, thus promoting the crop water consumption of maize [43]. Throughout the entire growth period, total ET_c from the 0–300 cm depth with VRT increased by 2.9% and 3.9% compared to DT and TT, respectively. This finding indicated that VRT promoted the crop water uptake by deepening tillage layers and reducing soil compaction, particularly during dry years [44]. In wet years (2021 and 2022), seasonal precipitation levels were sufficient, eliminating seasonal drought. However, compared to DT and TT, VRT treatment reduced SWS in the 0–300 cm layer to varying degrees, with reductions of 2.2% and 5.9% (2021), and 7.1% and 11.2% (2022), respectively. The result indicated that VRT led to reduced SWS in the 0–300 cm layer compared to DT and TT, giving rise to increased seasonal ET_c . These results align with previous findings that VRT increased the grain yield of winter wheat by increasing the crop water consumption in the 0–100 cm layer in the Huang-Huai-Hai Plain of China [45]. However, in a potato experiment on a semiarid Loess Plateau, the researchers suggested that the crop water consumption of VRT was not reduced compared to deep rotary tillage and traditional tillage [46]. This discrepancy may be due to the deeper tillage depth (0–300 cm vs. 0–200 cm in the potato experiment) of the deep vertical rotary tillage used in this study, facilitating root penetration and increasing the root uptake of soil moisture in the research areas [40]. Further research is necessary to explore the ecological effects on the mineralization losses of soil organic matter and the applicability of deep vertical rotary tillage in farmland across different climatic regions [35]. Nevertheless, in a 10-year located experiment, VRT showed great benefit in enhancing rainfall infiltration, decreasing soil evaporation, and guaranteeing the good conservation of soil water in dryland agriculture [30]. This actually increased the available soil water for crop growth in semi-arid areas of China, and was beneficial for the improvement of soil porosity [47]. In South Xinjiang, China, RVT was shown to improve soil conditions for saline farmland [17].

Applying appropriate tillage practices significantly enhances crop growth, development, and yield formation [48]. Research has shown that deep rotary tillage improved the environment for crop root growth, resulting in an increased above-ground dry matter accumulation [49]. Our findings indicated that, compared to DT and TT, plant dry matter accumulation increased when treated with VRT throughout the growth period of forage maize in 2020–2022, with an increase ranging from 5.6% to 12.8% at harvest. Previous studies have suggested that combining deep rotary tillage with plastic mulching enhanced ear length, ear diameter, kernel number per ear, and 100-kernel weight of maize, thereby promoting biomass and grain yield formation [50,51]. Our study was consistent with these findings, showing that VRT increased stem diameter by 3.4% to 7.6%, ear length by 1.7% to 7.3%, ear diameter by 0.6% to 3.2%, kernel number per ear by 4.2% to 13.2%, 100-kernel weight by 0.9% to 4.5%, and double ear rate by 27.9% to 51.5% in wet years, while reducing bald length by 11.3% to 38.1%. The correlation analysis also confirmed that VRT increased grain yield and WUE by enhancing the dry matter weight, ear length, kernel number per ear, and double ear rate. Consequently, it was concluded that deep vertical rotary tillage effectively promoted the dry matter accumulation and yield components of forage maize, greatly benefiting crop yield formation [52,53]. The study proved that the adoption of VRT optimized the soil environment for crop growth, facilitated the crop uptake of soil moisture,

and increased seasonal ET_c , consequently enhancing the biomass and grain yield of forage maize [54].

It was obvious that both climatic factors, primarily precipitation and tillage practices, played crucial roles in semiarid rain-fed conditions, influencing the biomass, grain yield, and WUE of forage maize [55]. Varied precipitation levels and distribution patterns significantly affected crop water consumption at different growth stages of forage maize [56]. During dry years with limited and unevenly distributed precipitation, VRT increased the total ET_c by 2.9% and 4.0% compared to DT and TT, respectively. Notably, VRT substantially elevated ET_c during the pre-flowering period by 13.9 to 20.3 mm. In the dry year of 2020, forage maize treated with VRT exhibited higher ET_c , suggesting that VRT could mitigate the risk of seasonal drought stress by enhancing soil water availability, and promoting crop water consumption [57], giving rise to a biomass and grain yield increase of 10.2% and 14.7%, respectively, and a WUE increase of 21.0% and 32.4% in dry years. Moreover, the correlation analysis indicated that the increase of SWS and ET_c positively affected the grain yield and WUE of forage maize. These outcomes indicated that, irrespective of precipitation years, the VRT technology enhanced forage maize growth and development by regulating ET_c and SWS, particularly in dry years with limited precipitation [58].

5. Conclusions

Deep vertical rotary tillage (VRT) enhances the soil environment for the root growth of forage maize by breaking plow pan, improving the absorption and utilization of deep soil moisture, and increasing soil water availability for crop growth. VRT effectively regulates crop water consumption, particularly during the pre-flowering period in dry years. Consequently, total soil water consumption increases throughout the entire growth period, promoting the accumulation of above-ground biomass, thus benefiting crop yield formation and enhancing WUE. Both grain yield and biomass yield increase with VRT treatment, with a more pronounced effect observed in dry years. In conclusion, deep vertical rotary tillage addresses the issues of soil compaction and shallow plow depth resulting from long-term traditional rotary tillage, thereby enhancing drought resistance and promoting the yield formation of forage maize in the semiarid areas of the Loess Plateau in northwest China.

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