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Effects of Different Tillage Depths on Soil Physical Properties and the Growth and Yield of Tobacco in the Mountainous Chongqing Region of China

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Abstract: Tobacco (*Nicotiana tabacum* L.) is the most important cash crop in the mountainous Chongqing region, where mini rotary tillers are widely used for land preparation. The decline in tobacco yields has been partially attributed to deteriorating soil physical properties and the formation of plough pans as a result of the repeated use of the mini rotary tiller. The objective of this study was to evaluate the effects of different tillage depths on soil physical properties and the growth and yield of tobacco. Three tillage depths were evaluated: mini rotary tillage to 15 cm (T15) as a control, medium-deep tillage to 25 cm (T25), and deep tillage to 35 cm (T35). Total porosity, capillary porosity, and soil water content were measured for each treatment, and the root distribution, agronomical traits, and dry matter accumulation were monitored at different growing stages. Tobacco yield and output value were determined following the harvest. Compared to T15, T35 significantly increased total porosity and capillary porosity in the 10–40 cm soil layer and soil water content in the 0–40 cm soil layer, while T25 improved soil physical properties but not significantly. T35 significantly promoted dry matter accumulation and root, stem, and leaf growth compared to T15, while differences in some agronomic traits between T25 and T15 were not significant. Compared to T15, T35 and T25 increased the tobacco yield by 17.2–18.9% and 8.0–10.1%, respectively, and increased the output value by 44.4–46.4% and 29.2–32.6%, respectively. The results indicate that deep tillage improves soil physical properties, breaks plough pans, stimulates root growth, and increases tobacco yield and output value.

Keywords: mini rotary tiller; total porosity; capillary porosity; root distribution; agronomic traits; tobacco

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1. Introduction

Tobacco (*Nicotiana tabacum* L.) is the most important cash crop in the mountainous regions of China, with a total plantation area of 6.7×10^5 ha in 2021, representing 66.5% of the total tobacco plantation area in China. Tobacco crop land in mountainous regions is commonly composed of small plots surrounded by high ridges. Therefore, a mini rotary tiller, developed for mountainous regions and with a tillage depth of 15 cm, is widely used for land preparation [1,2]. Long-term application of mini rotary tillers has seriously decreased the soil quality of cultivated land [3], resulting in the deterioration of soil physical properties and the formation of a plough pan at a depth of 20–30 cm [4,5]. Plough pan is characterized by a high bulk density, few macropores, and large mechanical impedance that reduces root growth [6], leads to difficulties related to crops achieving efficient absorption and utilization of soil water and nutrients, and consequently impacts the yield and quality of tobacco [1,7].

Deep tillage is considered an effective way to improve soil physical properties and increase crop yield [8]. Deep tillage can deepen the tillage thickness, improve soil physical properties, increase soil water retention capacity, create a large volume of loose soil for plant root growth, and stimulate plants to better absorb soil water and nutrients. It is therefore conducive to the growth and development of crops [4,9–11]. For example, Liu [1] found that, compared to 20-cm rotary tillage, 30-cm deep tillage and 40-cm subsoiling decreased soil bulk density at depths of 20–40 cm by 6.1 and 8.2%, increased soil capillary capacity by 11.3 and 21.6%, increased tobacco yield by 12.2 and 16.0%, and increased the output value by 10.5 and 21.8%, respectively. Hu et al. [12] investigated the response of soil aggregates, soil organic carbon (SOC), and root growth of tobacco to deep tillage in Southern China based on a 2-year field experiment. Compared to conventional rotary tillage to 12 cm, the 30-cm deep tillage increased the weight proportion of macroaggregates and SOC content in the 10–30 cm soil layer, improved the stability of soil aggregates in the 0–30 cm soil layer, and promoted root growth to extend down to the 30–40 cm soil layer. Gong et al. [13] evaluated the impacts of deep tillage (30 cm) and conventional rotary tillage (12 cm) on the growth and yield of tobacco in the dryland farming area of Hunan, China. Their results indicated deep tillage improved soil fertility, promoted vigorous growths of roots, stems, and leaves, and increased the quality and yield of tobacco. The effects of deep tillage on winter wheat [11], maize [7,11,14], cotton [6], cereal [15], legumes [16], watermelon [17], rice [18], stylo [7], tea [19], and sugarbeet [20] have also been studied. The main conclusions are that deep tillage reduces soil bulk density, improves aeration, breaks plough pans, promotes root growth, increases water and nutrient intake, and finally benefits crop growth and development.

Chongqing municipality, located in southwestern China, has an area of about 82,000 km^2, about 85% of which is mountainous. The annual plantation area of tobacco varied from 4.27×10^4 to 9.95×10^4 ha in the past three decades, and most tobacco farmland is in mountainous regions. Tobacco is one of the main sources of income for local farmers. The conventional tillage method and excessive application of chemical fertilizer have resulted in soil compaction and deterioration of soil physical properties. Tobacco disease and pests are on the rise, while tobacco yield and quality show a downward trend [21,22]. From 2011 to 2020, tobacco yield decreased from 1951.3 to 1800.1 kg ha^{-1} [22]. In addition, summer droughts, usually occurring in July and August, often lead to a reduction in tobacco yield. The plough pan formed by the conventional tillage method limits root growth and the absorption of soil water and nutrients from deep soil layers [23], which is not beneficial to tobacco survival during summer droughts. In the mountainous Chongqing region, plastic film mulching on the ridges is widely used for tobacco cultivation. The height of the ridge is about 30 cm, and the bottom width of the ridge is about 80 cm [24]. The purpose of forming the ridges is to increase the volume for root growth, and the plastic film mulch is used to increase the soil temperature in early spring to accelerate initial growth and to prevent soil and fertilizer losses [25]. However, whether deep tillage can improve soil physical properties and increase the yield and output value of tobacco under the conditions of ridge mulching cultivation in this mountainous region is not clear.

Therefore, the objective of this study was to evaluate the effects of different tillage methods on soil physical properties, tobacco growth, and yield under the ridge mulching cultivation systems employed in the mountainous Chongqing region.

2. Materials and Methods

2.1. Study Site

This study was conducted at the Runxi Tobacco Experimental Station of Pengshui Miao Autonomous County in Chongqing municipality, China. The experimental site was located at Liujiaping Village (108°05′90″ E, 29°12′39″ N), Huangjia Town, situated 1013 m AMSL. The climate is humid subtropical, with an average annual temperature of 15.8 °C and precipitation of 1380.0 mm (1951–2019). Precipitation has large inter-annual variability and an uneven seasonal distribution. The mean frost-free period is 290 d, and the mean duration of sunshine is 888.3 h per year. The soil in the study area has a silty clay loam texture [26], and sand, silt, and clay contents vary at different depths, with 2.2%, 57.3%, and 40.5% at the depth of 0–10 cm, 1.4%, 56.1%, and 42.5% at the depth of 10–20 cm, 1.6%, 60.8%, and 37.6% at the depth of 20–30 cm, and 2.3%, 62.2%, and 35.5% at the depth of 30–40 cm. The soil pH is 5.5, measured by the potentiometric method, and the organic matter content is 25.2 g kg^{-1}.

The field experiment was conducted in 2022 and 2023. The monthly precipitation and average temperature during the growing seasons of 2022 and 2023 are shown in Figure 1. The monthly rainfall in June, July, August, and September 2022 was much less than the corresponding mean values, reflecting a severe summer drought, while the monthly average temperatures in the early growing season of 2023 were less than the mean values, which impacted the normal growth of the tobacco crop.

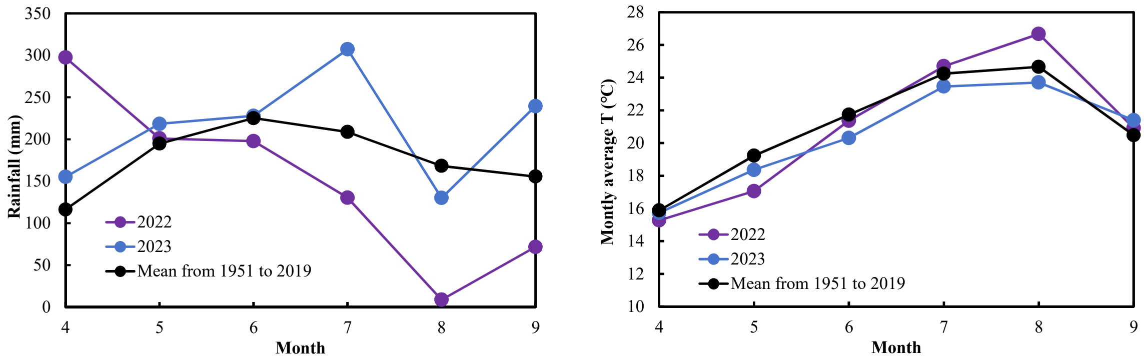

Figure 1. Monthly rainfall and average temperature during the growing seasons of 2022 and 2023 in comparison to mean values from 1951 to 2019.

2.2. Experimental Design

The experimental design featured three tillage treatments: shallow tillage to 15 cm (T15) as the control, medium-deep tillage to 25 cm (T25), and deep tillage to 35 cm (T35). A mini rotary tiller was used for T15 treatment, while a tracked rotary tiller was used for T25 and T35 treatments by adjusting plough depth. In all treatments, ridges with a height of 30 cm and a bottom width of 80 cm were constructed by machine and covered with black plastic film before seedling transplant. The total experimental area was 1350 m^2 divided into nine plots, each 15 m × 10 m in size. The treatments were replicated three times in a randomized, complete block design.

The tested tobacco variety was K326. This variety has a good quality of aroma and a high concentration of fragrance, and its annual plantation area is around 6.3×10^3 ha in the mountainous Chongqing region. The floating tray method was used to raise tobacco seedlings. All trays were perforated foam boards, with 3–5 tobacco seeds sown in each hole around the middle of March in a greenhouse. Transplanting took place on April 27 in 2022 and April 29 in 2023. Fertilization and other field management practices followed local tobacco leaf production technical procedures [27]. The combination of 700 kg ha^{-1} of chemical fertilizer ($N:P_2O_5:K_2O$ = 6:12:25), 1500 kg ha^{-1} of manure, and 300 kg ha^{-1} of sesame seed cake fertilizer were applied before ridging; 60 kg ha^{-1} of chemical fertilizer ($N:P_2O_5:K_2O$ = 20:15:10) was applied to the holes in the ridges to stimulate seedling growth when the seedlings were transplanted; and 195 kg ha^{-1} of potash fertilizer was again applied on day 30 after transplanting.

2.3. Field and Lab Measurements

2.3.1. Soil Physical Properties

Undisturbed soil samples were taken at each plot at four depths (0–10, 10–20, 20–30, and 30–40 cm) using standard pre-weighted 100 cm^3 Kopecki rings with a diameter of 5.046 cm and height of 5 cm for bulk density, total porosity, and capillary porosity determinations. Four replicated samples at each depth at each plot were collected at the dome stage on day 81 in 2022 and day 85 in 2023 after transplanting. One group of samples was used to measure soil bulk density by weight after drying in an oven at 105 °C for about 18–24 h [28], and another group was used to measure capillary porosity following the procedure described by Bao [29]. The undisturbed soil sample taken using a pre-weighed 100 cm^3 ring was wetted on a filter paper placed in a Petri dish, where the sides of the filter paper were dipped in water. The upper side of the ring was covered by a glass sheet in order to prevent evaporation. The sample was saturated until the upper surface of the sample becomes wet and shiny. This process was repeated a few times until the saturated sample reaches a stable weight. Capillary porosity was equal to the water weight divided by the sample volume. Soil total porosity was calculated using the following equation:

$$\rho = \left(1 - \frac{\text{Bulk density}}{\text{Particle density}}\right) \times 100\%, \quad (1)$$

where ρ is the total porosity (%). The Particle density at our experimental site was assumed to be 2.65 mg m^{-3}.

The mean bulk density, total porosity, and capillary porosity were calculated using six replications at each layer for each treatment.

Volumetric soil water content (SWC) was determined using calibrated time-domain reflectrometry (TDR) probes (Campbell Scientific Inc., Logan, UT, USA). The TDR probes were installed at five depths (5, 10, 20, 30, and 40 cm) in each plot and calibrated in the field under both dry and wet conditions against the calculated volumetric SWC of the collected samples. Measurements were made every 6 to 7 d. Monitoring of SWC was carried out from 25 April to 12 September in 2022 and from 25 April to 22 September in 2023. The mean SWC in the entire soil profile at each measurement time was calculated by weighting the SWC against the corresponding soil layer thickness. For each treatment, the mean SWC at each measurement time was calculated using three replications.

2.3.2. Spatial Distribution of Root Fresh Weight

In 2023, the vertical distribution of roots in the profile was determined using the 3D monolith method [1,30]. In this method, one plant sample was chosen in each plot, and the root zone from 0 to 50 cm was divided into five layers, each with a thickness of 10 cm. In each layer, nine 10 cm × 10 cm × 10 cm soil cubes were sampled around the plant. A total of 45 soil cubes were taken, with the root system of each excavated, cleaned, and the fresh weight measured. The spatial distribution of root fresh weight was determined based on the root weight in each soil cube and their locations around the plant. In addition, root fresh and dry weights at different stages were measured by excavating a soil volume of 30 cm length × 30 cm width × 50 cm depth in both years.

2.3.3. Agronomical Traits of Tobacco

According to the investigation and measurement methods for the agronomical traits of tobacco (YC/T 142–2010) issued by the China Tobacco Monopoly Bureau [31], a total of seven plants were randomly chosen and labeled from each experimental plot. The main agronomical traits, including plant height, stem girth, maximum leaf length, maximum leaf width, maximum leaf area, and effective leaf number in each plant, were measured at the rosette, flower budding, and dome stages. The maximum leaf area was calculated using the following empirical equation:

$$\text{Maximum leaf area} = \text{Maximum leaf length} \times \text{Maximum leaf width} \times 0.6345, \quad (2)$$

where 0.6345 is an empirical parameter determined by Wei et al. [32].

The mean and standard deviation for each characteristic were calculated based on 21 plants for each treatment.

2.3.4. Plant Dry Matter Accumulation

A total of five plants were randomly chosen from each experimental plot, with samples of roots, stems, and leaves taken from each plant at the rosette, flower budding, and dome stages. Fresh weights were measured, and then all fresh samples were oven dried at 105 °C for 15 min and then at 60 °C for 10–12 h to obtain dry matter weights. The total dry weight of each plant was the sum of values obtained for roots, stems, and leaves.

2.3.5. Yield and Output Value

In each experimental plot, 16 tobacco plants were selected for baking. According to the national standard (GB2635–92 [33]), tobacco yield and the proportions of superior and medium-grade leaves were calculated for individual plants, and then these indices were converted into per-hectare values based on the area occupied by the selected tobacco plants. The output value was calculated according to leaf yield, quality, and market price for leaves of different grades.

2.4. Statistical Analysis

Excel 2021 was used for statistical analysis and tabulation of the data. SPSS 22.0 (SPSS Inc., Chicago, IL, USA) was used to identify significant differences between the treatments using paired *t*-tests; multiple comparisons were made using Duncan's multiple range test (MRT) with $p < 0.05$.

3. Results

3.1. Soil Physical Properties

With the exception of the surface soil layer (0–10 cm), total porosity was significantly influenced by tillage depth (Figure 2). Compared to T15, T35 significantly increased total porosity at depths of 10–20, 20–30, and 30–40 cm in the two consecutive years considered. The increase varied from 6.3 to 8.9% in 2022 and from 2.3 to 11.2% in 2023, with the largest difference in total porosity between T35 and T15 occurring at a depth of 30–40 cm in both years. Although the differences in total porosity between T35 and T25 and between T25 and T15 were not significant at each depth, the deeper tillage always resulted in greater total porosity at each depth. For all treatments, total porosities decreased with increasing depth. The larger decrease in total porosity occurred at a depth of 20–30 cm for T15 (Figure 2), which reflected the position of the plough pan created by the traditional tillage method.

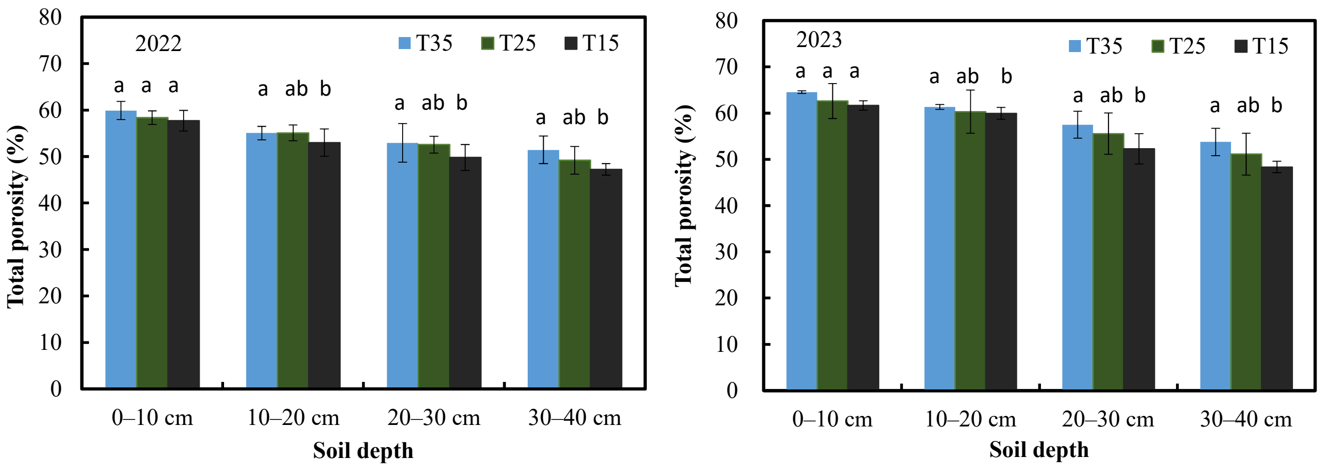

Figure 2. Differences in total porosity at different depths for the three tillage treatments. For a given soil depth, soil porosities labeled with different letters are significantly different according to Duncan's MRT ($p > 0.05$).

Similar to total porosity, capillary porosities at depths of 10–20, 20–30, and 30–40 cm were also significantly influenced by tillage depth. Among the three treatments, the differences in capillary porosity between T35 and T15 were only significant at depths of 10–20, 20–30, and 30–40 cm (Figure 3), with the largest difference occurring at a depth of 20–30 cm in both years due to the effect of the plough pan. Unlike total porosity, capillary porosity increased with depth for all treatments due to decreasing macropores in the deeper soil.

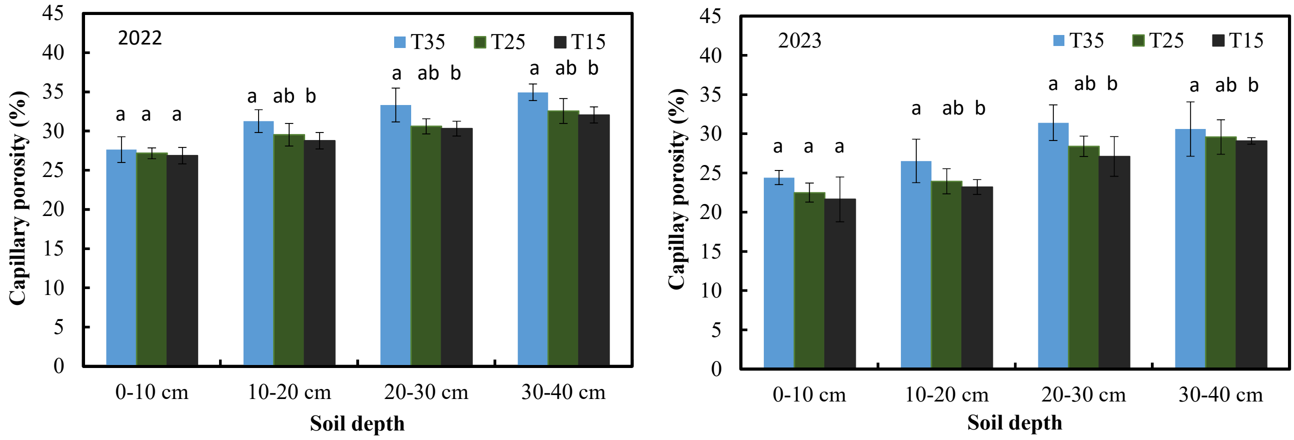

Figure 3. Differences in the measured capillary water capacity at different depths for the three tillage treatments. For a given soil depth, capillary porosities labeled with different letters are significantly different according to Duncan's MRT ($p > 0.05$).

Different tillage depths also influenced SWC during the growing seasons, with the highest values observed in T35 (Figure 4). Moreover, 2022 was a dry year and featured a long (June–September) and severe (46.0% reduction in precipitation) summer drought (Figure 1). The soil subjected to the T35 treatment had a larger SWC, with an average of 0.265 cm^3 cm^{-3} in the 0–40 cm profile throughout the growing season. Compared to T15 and T25, T35 increased soil water storage by 15.2 and 10.4%, respectively, which was very important for the tobacco crop to survive the summer drought. T25 was not as effective as T35, as it only increased soil moisture storage by 4.3% compared to T15. Moreover, 2023 was a slightly wet year, with 19.6% more rainfall than average throughout the growing season. T35 increased soil moisture in the 0–40 cm profile by 11.5 and 4.8% compared to T15 and T25, respectively. Therefore, T35 improved the hydrological soil properties and increased moisture retention during the growing period of both years. This is attributed to T35 increasing the capillary porosity to capture and store more moisture compared to T15 and T25.

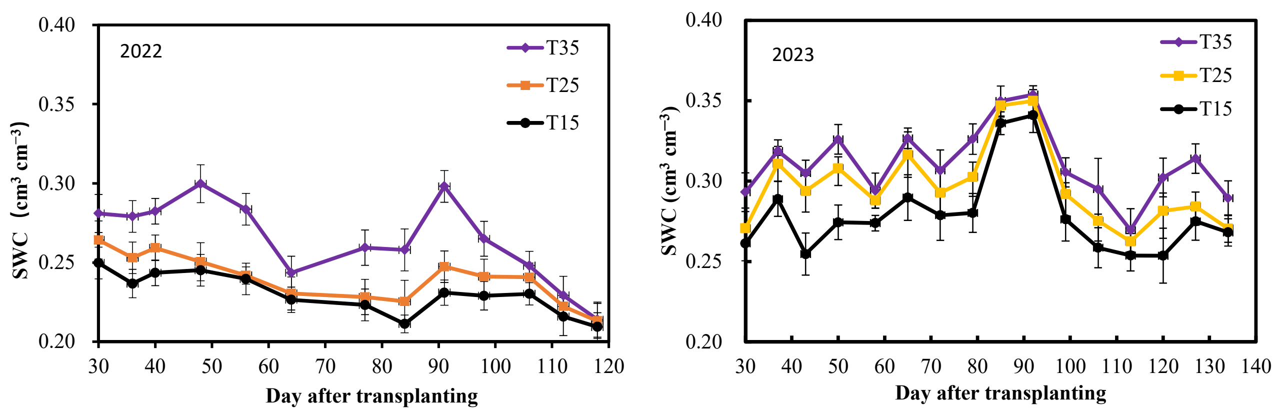

Figure 4. Changes in average SWC in the 0–40 cm profile for the three tillage treatments during the growing seasons of 2022 and 2023.

3.2. Root Growth and Spatial Distribution

As shown in Figure 5, the responses of root growth to different tillage treatments were significantly different in both years. Among the three tillage treatments, T35 significantly stimulated root growth compared to T25 and T15 throughout the growing seasons, while root growth was not significantly different between T25 and T15. For example, in 2022, the root fresh weight under the T35 treatment was 53.0, 111.3, and 251.8 g at the rosette, flower budding, and dome stages, representing increases of 28.0, 16.1, and 19.9% compared to T25 and 34.9, 33.3, and 22.2% compared to T15, respectively. In addition, the growth rate of the root system under the T35 treatment was larger than under both the T25 and T15 treatments. For example, in 2023, the growth rate of the root system from the rosette stage to the dome stage was 9.3, 8.3, and 7.8 g d^{-1} for T35, T25, and T15, respectively.

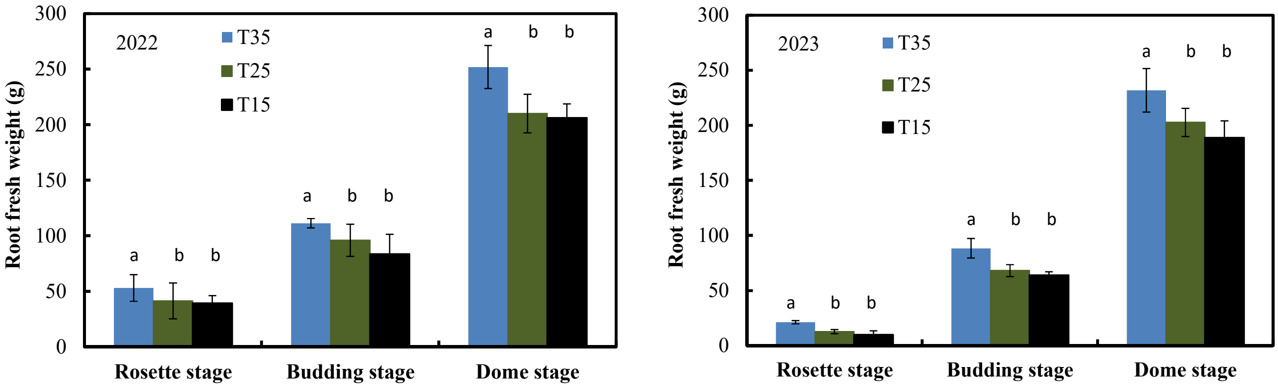

Figure 5. Differences in the measured root fresh weight at different stages for the three tillage treatments. For a given stage, root fresh weights labeled with different letters are significantly different according to Duncan's MRT ($p > 0.05$).

Deep tillage increased the root fresh weight and promoted vertical growth of the tobacco root system, which consequently resulted in better spatial distribution of the roots. We measured the spatial distribution of root fresh weight in a 30 cm × 30 cm × 50 cm soil volume (Figure 6). Compared to the T15 shallow treatment, medium-deep tillage and deep tillage increased the root distribution at depths of 20–30, 30–40, and 40–50 cm and decreased the root distribution at depths of 10–20 cm. For example, the proportion of root fresh weight at depths of 20–30, 30–40, and 40–50 cm was 9.5, 0.6, and 0.2% for T15; 10.2, 0.9, and 0.3% for T25; and 11.6, 1.1, and 0.5% for T35, respectively. Meanwhile, the proportion of root fresh weight at a depth of 10–20 cm was 56.1% for T15, 53.5% for T25, and 47.7% for T35. These findings indicate deep tillage also alleviates crowding in the upper root system.

3.3. Agronomic Traits

Table 1 shows the effect of different tillage depths on tobacco agronomic traits. In 2022, T35 and T25 resulted in significant increases in plant height, stem girth (dome stage only), maximum leaf area, and effective leaf number at all three stages compared to T15; no significant differences in any agronomic traits were noted between the T35 and T25 treatments. At the dome stage, the maximum leaf area and effective leaf number increased by 18.5 and 12.9% for T35 and by 17.2 and 6.5% for T25 compared to T15.

In 2023, significant differences between T35 and T15 were noted for plant height, stem girth, and maximum leaf area at the three stages, and for effective leaf number only at the budding and dome stages. Stem girth and maximum leaf area were significantly larger for T25 than T15 at all stages, while plant height and effective leaf number varied between T25 and T15 at different growing stages. In general, tillage treatments significantly influenced tobacco agronomic traits, with deeper tillage stimulating tobacco growth and development, especially at the flower budding and dome stages.

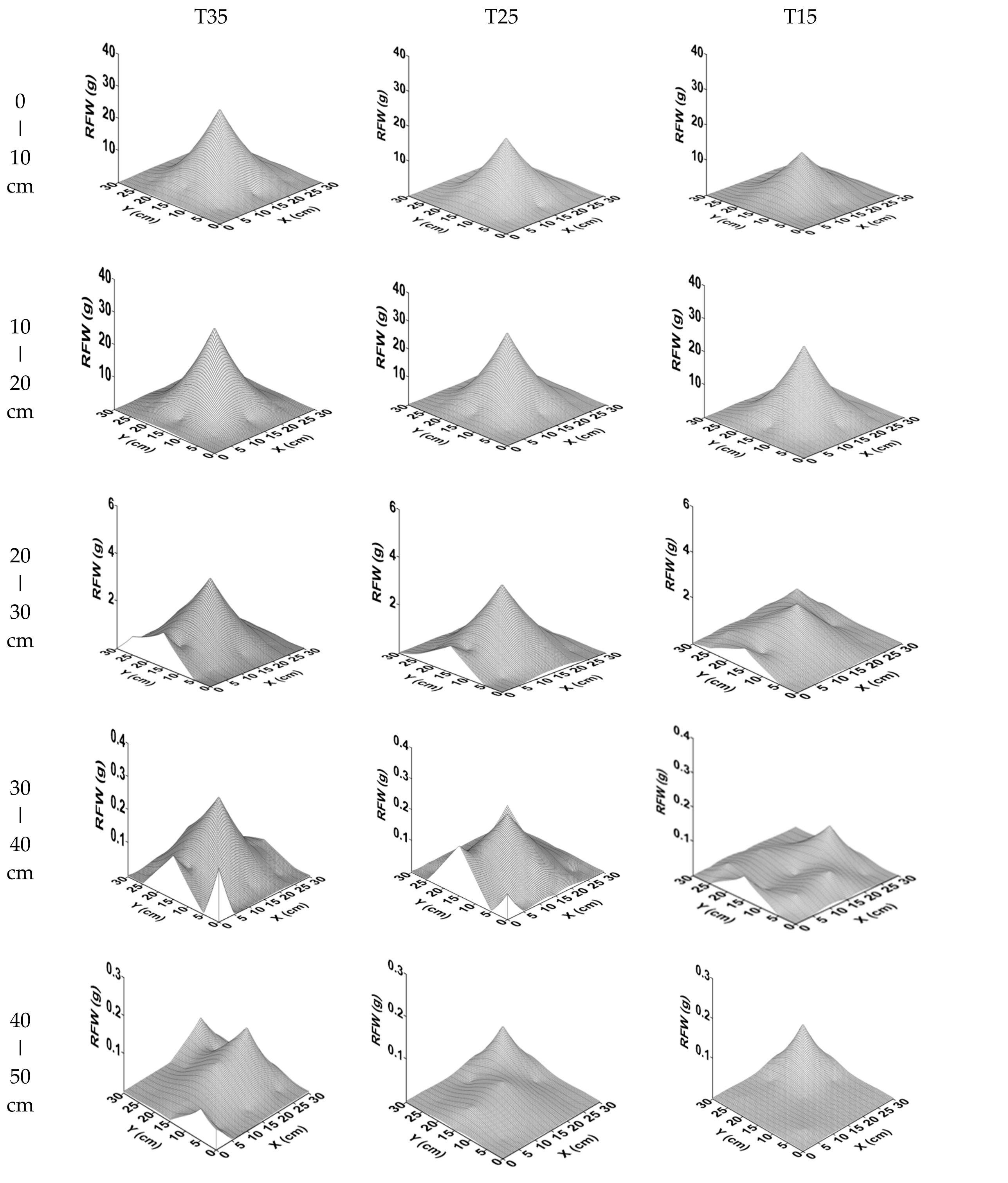

Figure 6. Effects of different tillage treatments on the spatial distribution of root fresh weight (RFW, g) at soil depths of 0–10, 10–20, 20–30, 30–40, and 40–50 cm.

3.4. Dry Matter Accumulation

Among the three treatments, the rate of total dry matter accumulation was the fastest for T35 during the growing season of both years, with values of 7.5 g d^{-1} in 2022 and 7.6 g d^{-1} in 2023 compared to 6.4 g d^{-1} in 2022 and 7.0 g d^{-1} in 2023 for T25 and 6.1 g d^{-1} in 2022 and 4.4 g d^{-1} in 2023 for T15. For all sampling stages, significant differences in the total plant dry weight were noted between T35 and T15 and between T25 and T15 in both years (Table 2), while total dry matter weight was not significantly different between T35 and T25 at most sampling stages. The same trend was observed in root, stem, and leaf dry weights. Among the three sampling stages, the effects of the T35 and T25 treatments on dry weight accumulation were more pronounced at later growing stages, especially with respect to leaves, when the demand for nutrients and water was high.

Table 1. Effects of different tillage treatments on the agronomic traits of tobacco.

Year	Growing Stage	Treatment	Plant Height (cm)	Stem Girth (cm)	Maximum Leaf Area (cm^2)	Effective Leaf Number
2022	Rosette stage	T35	26.1 ± 0.2 a	7.6 ± 0.2 a	949.2 ± 41.1 a	18.0 ± 0.0 a
		T25	26.4 ± 0.4 a	8.0 ± 0.1 a	948.7 ± 123.4 a	17.5 ± 0.7 a
		T15	22.7 ± 0.6 b	7.5 ± 0.4 a	859.3 ± 36.2 b	14.5 ± 0.0 b
	Budding stage	T35	68.2 ± 0.1 a	8.8 ± 0.1 a	1266.5 ± 26.7 a	17.8 ± 1.1 a
		T25	66.1 ± 0.6 a	8.8 ± 0.0 a	1261.3 ± 31.8 a	16.3 ± 0.4 a
		T15	60.5 ± 0.5 b	8.7 ± 0.1 a	1162.7 ± 68.9 b	14.3 ± 0.4 b
	Dome stage	T35	106.0 ± 2.8 a	10.6 ± 0.5 a	1391.3 ± 68.6 a	17.5 ± 0.7 a
		T25	105.8 ± 2.8 a	10.4 ± 0.2 a	1376.7 ± 24.5 a	16.5 ± 0.0 a
		T15	94.4 ± 3.8 b	10.1 ± 0.1 b	1174.4 ± 40.4 b	15.5 ± 0.7 b
2023	Rosette stage	T35	26.5 ± 2.7 a	7.8 ± 0.1 a	1522.2 ± 72.8 a	13.3 ± 1.7 a
		T25	25.2 ± 0.7 a	7.8 ± 0.1 a	1392.9 ± 73.7 a	13.7 ± 1.2 a
		T15	23.1 ± 0.5 b	7.5 ± 0.2 b	1295.7 ± 32.2 b	13.0 ± 0.6 a
	Budding stage	T35	61.7 ± 6.1 a	8.7 ± 0.2 a	1677.3 ± 29.3 a	16.5 ± 1.0 a
		T25	57.7 ± 2.2 b	8.8 ± 0.1 a	1629.1 ± 35.4 a	16.0 ± 0.0 a
		T15	54.2 ± 1.8 b	8.5 ± 0.1 b	1456.7 ± 19.3 b	14.0 ± 1.6 b
	Dome stage	T35	102.3 ± 7.7 a	10.9 ± 0.7 a	1841.3 ± 45.3 a	18.1 ± 1.0 a
		T25	94.3 ± 1.8 ab	10.6 ± 0.1 a	1775.4 ± 41.9 a	18.0 ± 1.0 a
		T15	91.5 ± 0.9 b	10.0 ± 0.2 b	1534.3 ± 21.4 b	15.7 ± 1.2 b

Note: At each stage, values within a column followed by different letters are significantly different according to Duncan's MRT ($p > 0.05$).

Table 2. Effects of different tillage treatments on the dry matter of different parts of tobacco plants.

Year	Growing Stage	Treatment	Root (g)	Stem (g)	Leaf (g)	Total (g Plant^{-1})
2022	Rosette stage	T35	9.7 ± 0.4 a	11.6 ± 2.2 a	42.1 ± 8.0 a	62.3 ± 9.8 a
		T25	8.4 ± 2.4 b	10.0 ± 0.0 a	41.4 ± 0.9 a	60.8 ± 3.3 a
		T15	6.9 ± 2.4 b	9.0 ± 1.5 b	35.5 ± 10.7 b	51.3 ± 14.6 b
	Budding stage	T35	22.6 ± 3.6 a	27.3 ± 1.0 a	83.3 ± 4.7 a	133.2 ± 9.3 a
		T25	19.6 ± 0.8 b	27.9 ± 1.2 a	82.3 ± 1.6 a	129.8 ± 0.4 a
		T15	17.2 ± 6.2 b	21.6 ± 5.6 b	76.9 ± 17 b	115.7 ± 28.8 b
	Dome stage	T35	60.8 ± 19.8 a	82.8 ± 3.7 a	128.3 ± 10.4 a	271.9 ± 36.5 a
		T25	55.4 ± 0.4 b	69.3 ± 8.9 b	116.6 ± 16.8 b	241.3 ± 17.5 b
		T15	51.3 ± 2.5 b	62.7 ± 6.9 b	97.9 ± 5.6 c	221.9 ± 3.8 c
2023	Rosette stage	T35	2.0 ± 0.6 a	1.7 ± 0.4 a	10.2 ± 3.0 a	13.9 ± 4.0 a
		T25	1.6 ± 0.3 b	1.6 ± 0.8 a	9.6 ± 2.5 a	12.8 ± 3.0 a
		T15	1.2 ± 0.5 b	0.9 ± 0.4 b	7.8 ± 2.3 b	9.9 ± 4.3 b
	Budding stage	T35	18.6 ± 12.0 a	18.1 ± 6.1 a	58.0 ± 11.9 a	94.6 ± 30.0 a
		T25	11.3 ± 0.6 b	15.0 ± 0.5 b	48.8 ± 1.3 b	75.0 ± 2.5 b
		T15	10.5 ± 0.5 b	10.8 ± 0.6 c	44.6 ± 0.5 c	65.9 ± 0.5 c
	Dome stage	T35	67.7 ± 19.7 a	62.4 ± 10.7 a	96.6 ± 13.2 a	225.7 ± 12.1 a
		T25	60.8 ± 1.1 b	52.9 ± 1.8 b	93.8 ± 2.8 b	207.5 ± 5.7 b
		T15	52.9 ± 13.8 b	40.1 ± 13.3 c	59.4 ± 25 c	132.3 ± 10.2 c

Note: At each stage, values within a column followed by different letters are significantly different according to Duncan's MRT ($p > 0.05$).

3.5. Yield and Output Values

Table 3 shows the tobacco yield for T35 was the highest among the three treatments in each year, reaching 2311.5 kg ha^{-1} in 2022 and 2210.5 kg ha^{-1} in 2023 and being 6.9–10.1

and 17.9–18.9% larger than for T25 and T15, respectively. The difference in tobacco yield between T35 and T15 and between T25 and T15 was significant in both years; the difference between T35 and T25 was not significant in 2022 and significant in 2023.

Table 3. Effects of different tillage depths on tobacco yield and output value.

	2022			2023		
Treatment	**Yield (kg ha^{-1})**	**Output Value (CNY ha^{-1})**	**Proportion of Medium and Superior Grade Leaves (%)**	**Yield (kg ha^{-1})**	**Output Value (CNY ha^{-1})**	**Proportion of Medium and Superior Grade Leaves (%)**
T35	2311.5 ± 263.6 a	68,742.0 ± 9272.6 a	95.5 ± 1.7 a	2210.5 ± 18.3 a	63,973.0 ± 918.7 a	94.2 ± 1.2 a
T25	2100.0 ± 166.9 a	60,666.0 ± 4972.5 a	91.1 ± 2.8 a	2068.2 ± 74.1 b	58,838.8 ± 1298.0 b	92.7 ± 2.1 a
T15	1944.0 ± 203.3 b	46,941.0 ± 5903.7 b	81.5 ± 5.2 b	1875.6 ± 21.4 c	44,585.1 ± 982.3 c	74.4 ± 4.5 b

Note: The definition of CNY is the Chinese Yuan; within a column, values followed by different letters are significantly different according to Duncan's MRT ($p > 0.05$).

Compared to T15, T35 and T25 significantly increased the proportions of medium- and superior-grade leaves in both years. Among the three treatments, the proportion of medium- and superior-grade leaves was the highest for T35, at 95.5% in 2022 and 94.2% in 2023, representing an increase of 1.6–4.8% compared to T25 and 17.2–26.6% compared to T15.

Due to the highest yield and the largest proportion of medium- and superior-grade leaves, the output value for the T35 treatment was significantly higher than for the T25 and T15 treatments, reaching 68742.0 CNY ha^{-1} in 2022 and 63973.0 CNY ha^{-1} in 2023. Similar to yield, the difference in the output value between T35 and T25 was not significant in 2022 and was significant in 2023. This is attributed to the cumulative effect of two consecutive years of deep tillage.

4. Discussion

Chongqing municipality is one of the main tobacco production regions in China. The main features of the Chongqing tobacco production region are that: (1) all tobacco farmlands are located in remote mountainous regions without convenient transportation; (2) tobacco farmland is composed of small and uneven plots, usually surrounded by high ridges; (3) the soil thickness in the mountainous tobacco fields is thin, usually less than 100 cm; and (4) tobacco farmlands are decentralized and owned by individual peasant households. A type of mini rotary tiller with a tillage depth of 15 cm is widely used for land preparation [1,2]. Long-term applications of mini rotary tillers and excessive chemical fertilizer have resulted in the deterioration of soil physical properties. The results of our field experiment conducted over two consecutive years verify that, compared to the traditional approach with shallow tillage to 15 cm, deep tillage to 35 cm can significantly decrease soil bulk density and increase total porosity and capillary porosity at depths of 10–40 cm (Figures 2 and 3). The increased soil capillary porosity at depths of 10–40 cm can consequently improve soil water storage in the 0–40 cm profile (Figure 4), which helps tobacco crops survive summer droughts. Similar results have been reported by Wang et al. [23] and Hassan et al. [34], who attribute the increase in soil water storage under deep tillage treatment to improvements in soil total porosity, capillary porosity, soil permeability, and infiltration depth by breaking the plough pan [35–37].

No significant difference in total porosity and capillary porosity at a depth of 0–10 cm could be attributed to the impact of tobacco cultivation activities. In the study site, plastic film mulching on the ridge was used for tobacco cultivation, and the film on both sides of the ridge was covered by 1–2 mm of soil for fixing the film. This process was operated by machines and could alter the physical properties of the topsoil. In this study, soil total porosity decreased with increasing soil depth for all treatments. The main reason was that soil compaction resulted in an increase in bulk density with increasing soil depth. The same results have been reported by Adeoye and Mohamed-Saleem [7] and Lipiec et al. [38].

The results of this study indicate deep tillage to 35 cm can improve the growth environment of the tobacco root system, significantly increase the volume of tobacco root growth (Figure 5), and result in greater spatial distribution of roots by alleviating crowding in the upper root system (Figure 6). The assumption is that deep tillage can increase total porosity (Figure 2) and reduce soil bulk density and penetration resistance, resulting in increased soil ventilation and reduced root growth resistance [39]. Wang et al. [40], Dong et al. [2], and Liu et al. [41] also report similar results, in which deep tillage simulates root growth by increasing the number of lateral roots, expanding root growing space, and decreasing root growth resistance. In this study, root fresh weights at the rosette and budding stages were larger in 2022 than in 2023 for each treatment (Figure 5). The lower monthly rainfall after May 2022 than in 2023 promoted root growth to uptake water from the deep layer (Figure 1). Tobacco agronomic traits and dry matter accumulation in different organs are important indicators that reflect plant growth status and determine the tobacco yield and output value [42]. In this study, deep tillage to 35 cm significantly increased plant height, stem girth, maximum leaf area, and leaf number at the flower budding and dome stages compared to shallow tillage to 15 cm (Table 1). Dry matter accumulation of root, stem, and leaf tissue was significantly higher under the deep tillage treatment compared to the shallow tillage treatment (Table 2). This is attributed to the improved soil physical properties stimulating root growth and facilitating the absorption of more water and nutrients from the deep soil [36], thus promoting the supply of nutrients and water to aboveground parts by the roots, enhancing photosynthesis and respiration, accelerating cell division, increasing nitrate reductase activity, and ultimately helping to improve all agronomic traits [43–45] and dry matter accumulation [41,46,47].

The results of this study show deep tillage to 35 cm can significantly increase tobacco yield and result in economic benefits, similar to the results reported by Lu et al. [48], Sun et al. [49], Botta et al. [50], and Peng et al. [51]. Deep tillage can improve soil physical properties and help soil store more water and nitrogen, with sufficient water and nutrients then promoting crop growth and ultimately yield, which is in accordance with the general concept that water and nutrient availability are important for crop production [4,52–56]. Tobacco yield was slightly higher in dry 2022 than wetter 2023 for each treatment (Table 3). In the mountainous Chongqing region, almost all climate variables influence tobacco growth and yield, but their important degrees are different. Yang [57] reports that the important degree occurs in the order of sunlight hours > air temperature > precipitation at our study site. The total sunlight hours during the growing season should be larger in dry 2022 than wetter 2023, whereas the average air temperature was higher in dry 2022 than wetter 2023 (Figure 1). Both variables resulted in a slightly larger tobacco yield in dry 2022 than wetter 2023. Deep subsoiling also significantly increases the proportion of medium and superior tobacco leaves. This is attributed to deep tillage improving soil aeration and stimulating root growth, which promotes nitrogen absorption and utilization by tobacco at early stages and reduces the nicotine content in the medium and superior leaves [58].

5. Conclusions

This field experiment conducted over two consecutive years with three tillage treatments (mini rotary tillage to 15 cm, medium-deep tillage to 25 cm, and deep tillage to 35 cm) detailed and analyzed the responses of soil physical properties, tobacco agronomic traits, root growth, plant dry matter accumulation, yield, and output value to tillage depth. The following conclusions can be drawn:

(1) Deep tillage improves soil physical properties by increasing total porosity, capillary porosity, and soil water content in the 0–40 cm profile.

(2) Deep tillage significantly simulates root growth and improves root spatial distribution, which is beneficial as it facilitates the absorption of water and nutrients by tobacco plants from deep soil layers.

(3) Deep tillage significantly optimizes tobacco agronomic traits and promotes tobacco growth, development, and dry matter accumulation.
(4) Deep tillage significantly increases tobacco yield and the proportion of medium-superior-grade leaves and consequently results in higher output values compared to tillage at traditional depths.

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