Effects of Different Tillage Depths on Soil Physical Properties and Spatial Distribution Characteristics of Flue-Cured Tobacco Root System Postprint

Authors: Tong Wenjie, Deng Xiaopeng, Xu Zhaoli, Ma Erdeng, Jin Yan, Junying Li

Date: 2017-11-07T00:00:00+00:00

Abstract

To investigate the effects of different tillage depths on flue-cured tobacco yield and output value and to reveal the mechanisms through which deep tillage increases yield and efficiency in tobacco fields, a field location experiment was conducted using the flue-cured tobacco variety 'K326' as experimental material. Three treatments were established: control tillage at 20 cm (GS20), tillage at 30 cm (GS30), and tillage at 40 cm (GS40), to examine the effects of different tillage depths on leaf yield and output value, soil physical properties, and spatial distribution characteristics of flue-cured tobacco roots. The results indicated that deep tillage measures produced beneficial effects on improving soil structure, promoting soil water storage, optimizing flue-cured tobacco root architecture, and increasing leaf yield and output value. Deep tillage treatments significantly reduced soil bulk density in the 20–40 cm subsurface layer while significantly increasing both total porosity and capillary porosity in this horizon. Specifically, compared with the GS20 treatment, GS30 and GS40 reduced soil bulk density by 8.4% and 9.4%, increased total porosity by 15.6% and 13.1%, and increased capillary porosity by 25.8% and 24.8%, respectively. Relative to the control GS20, GS30 and GS40 significantly increased soil water content in the 0–20 cm surface layer at the rosette stage and significantly enhanced soil water content in the 20–40 cm subsurface layer during the vigorous growth and maturity stages. Deep tillage treatments not only significantly increased the absolute quantity of flue-cured tobacco roots but also promoted root growth into deeper soil strata, thereby elevating the root depth index of flue-cured tobacco. Specifically, the fresh weight of root biomass in GS30 and GS40 was 31.2% and 89.2% higher than that in GS20, respectively, while the root depth index increased by 7.6% and 4.5%, respectively. Compared with the control GS20, GS30 and GS40 increased leaf yield by 7.0% and 27.3%, average price by 1.8% and 6.2%, the proportion of high-grade tobacco by 10.4% and 24.4%, and output value by 9.0% and 35.1%, respectively, with significant differences observed between GS40 and GS20. The study revealed that deep tillage measures first modify soil physical structures such as bulk density and porosity, subsequently influence soil water storage and entropy in tobacco fields, promote early growth and rapid development of flue-cured tobacco, optimize the spatial distribution architecture of tobacco roots, then affect aboveground morphological establishment, and ultimately determine leaf yield and output value.

Full Text

Preamble

Chinese Journal of Eco-Agriculture, Nov. 2016, 24(11): 1464−1472
Effect of Plowing Depth on Soil Physical Characteristics and Spatial Distribution of Flue-Cured Tobacco Root System

TONG Wenjie, DENG Xiaopeng, XU Zhaoli, MA Erdeng, JIN Yan, LI Junying**
(Yunnan Academy of Tobacco Agricultural Sciences, Kunming 650021, China)

Abstract

To investigate the effects of different plowing depths on flue-cured tobacco yield and output value and to reveal the underlying mechanisms of yield increase and efficiency improvement through deep plowing in tobacco fields, a field experiment was conducted using the flue-cured tobacco variety 'K326'. Three treatments were established: conventional tillage at 20 cm (GS20), deep tillage at 30 cm (GS30), and deep tillage at 40 cm (GS40). The effects of different plowing depths on tobacco leaf yield and output value, soil physical properties, and spatial distribution characteristics of the flue-cured tobacco root system were studied. The results demonstrated that deep plowing effectively improved soil structure, enhanced water storage, optimized root system architecture, and increased tobacco leaf yield and output value. Deep plowing significantly reduced soil bulk density in the 20–40 cm subsurface layer while significantly increasing total porosity and capillary porosity in this layer. Compared with GS20, GS30 and GS40 reduced soil bulk density by 8.4% and 9.4%, increased total porosity by 15.6% and 13.1%, and increased capillary porosity by 25.8% and 24.8%, respectively. Relative to GS20, GS30 and GS40 significantly increased soil water content in the 0–20 cm surface layer during the rosette stage and in the 20–40 cm subsurface layer during the vigorous growth and maturation stages. Deep plowing not only significantly increased the absolute quantity of tobacco roots but also promoted root growth into deeper soil layers, thereby increasing the root depth index. Root fresh biomass weight under GS30 and GS40 was 31.2% and 89.2% higher than under GS20, respectively, while the root depth index increased by 7.6% and 4.5%, respectively. Compared with

GS20, GS30 and GS40 increased tobacco leaf yield by 7.0% and 27.3%, average price by 1.8% and 6.2%, the proportion of high-quality tobacco by 10.4% and 24.4%, and output value by 9.0% and 35.1%, respectively, with significant differences observed between GS40 and GS20. The study revealed that deep plowing first modifies soil physical structure such as bulk density and porosity, which subsequently affects soil water storage and temperature, promotes early and rapid tobacco seedling growth, optimizes the spatial distribution pattern of the tobacco root system, influences aboveground morphological development, and ultimately affects tobacco leaf yield and output value.

Keywords: Deep plowing; Flue-cured tobacco; Soil physical characteristics; Spatial distribution of root system; Yield and output value

Introduction

Flue-cured tobacco is an important economic crop in Yunnan Province, with its planting area and production accounting for more than one-third of the national total, occupying a significant position in China' s tobacco (*Nicotiana tabacum* L.) industry. Currently, farmland in Southwest China primarily relies on small-power machinery for shallow plowing at 15–25 cm depth, with an average tillage layer thickness of 18.2 cm—nearly 5 cm shallower than during the second national soil survey period and far from the 35 cm tillage thickness typical of U.S. farmland [1]. Similar conditions exist in Yunnan' s tobacco-growing soils, where long-term single shallow plowing has led to increasingly prominent structural problems: a markedly shallow tillage layer, significantly reduced effective tillage soil volume, soil compaction, and a thickened and upward-shifted plow pan [2]. Imbalanced tillage structure severely constrains water and nutrient storage capacity in tobacco fields, affects early and rapid root development after transplanting, hinders root distribution in deep soil layers, and impacts field tolerance during later growth stages. Xu et al. [3] identified shallow tillage layers and inadequate root development as primary reasons for lower tobacco quality in Southwest China compared to high-quality foreign tobacco.

Crop root size and spatial distribution architecture are closely related to the ability of crops to absorb soil water and mineral elements [4-6]. Modern tillage practices such as deep plowing or subsoiling can break plow pan barriers, reduce soil bulk density, regulate soil solid-liquid-gas phase ratios, increase effective soil pores, and improve water storage capacity, creating a coordinated soil environment for root growth [7]. Previous research has extensively investigated crop growth and development, but most studies have focused on soil physicochemical property improvement or aboveground growth [8-9], with limited quantitative research on horizontal extension and vertical growth of underground roots under deep tillage conditions. The root system is the primary organ for tobacco to absorb soil water and nutrients and to synthesize plant hormones, nicotine, and some amino acids, making it a crucial contributor to tobacco leaf yield and quality formation. Tobacco root growth, development, and spatial architecture are closely related to the tillage layer soil environment [10]; however, quantitative research in this area remains scarce. Based on field experiments, this study investigated the effects of different tillage depths on soil physicochemical properties, root spatial distribution characteristics, and flue-cured tobacco growth, development, yield, and output value. From the perspective of the tobacco root-soil system, we explored the yield-increasing and efficiency-enhancing mechanisms of deep plowing in tobacco fields to provide a theoretical basis for efficient tobacco cultivation.

1.1 Study Area Overview

The experiment was conducted in 2015 at the Jiuxi Tobacco Experimental Base in Jiangchuan County, Yuxi City, Yunnan Province (24°18 N, 102°38 E). The experimental area has an average annual temperature of 14.3–16.6°C, average annual precipitation of 706.3–1,088.3 mm, and annual sunshine hours of 2,075.2 h. The experimental site practiced a flue-cured tobacco-rice rotation with winter fallow. The soil type was light loam, and basic physicochemical properties before plowing are shown in .

1.2 Experimental Design

The test material was the local conventional cultivar ‘K326’ . A single-factor randomized block design was employed, with three tillage depth treatments established by controlling moldboard plow height via tractor hydraulics: 20 cm tillage depth (control, GS20), 30 cm tillage depth (GS30), and 40 cm tillage depth (GS40). Each treatment had three replications, totaling nine plots, with each plot area of 192 m^2 (9.6 m × 20 m). Plant and row spacing were 0.5 m and 1.2 m, respectively. Tobacco seedlings were transplanted on April 24. Before transplanting, compound fertilizer (300 $kg \cdot hm^{-2}$) and calcium-magnesium phosphate fertilizer (375 $kg \cdot hm^{-2}$) were applied in planting holes. Ten days after transplanting, nitrogen-potassium fertilizer (150 $kg \cdot hm^{-2}$) and boron-zinc fertilizer (3 $kg \cdot hm^{-2}$) were applied with water. Thirty days after transplanting, compound fertilizer (300 $kg \cdot hm^{-2}$), nitrogen-potassium fertilizer (150 $kg \cdot hm^{-2}$), and potassium sulfate (150 $kg \cdot hm^{-2}$) were applied with water. Intertillage and hilling were performed 35 days after transplanting, with a ridge height of 35 cm. Pest and disease control and other field management practices followed local high-quality tobacco production management protocols.

1.3.1 Leaf Area Index and Yield

During the rosette stage (30 days after transplanting), early vigorous growth stage (45 days after transplanting), late vigorous growth stage (60 days after transplanting), and early maturation stage (75 days after transplanting), one representative plant was selected in each plot for full-leaf labeling. Leaf area index was calculated according to the China Tobacco Industry Standard (YC/T 142—1998) as: Leaf Area Index = Leaf Length (cm) × Leaf Width (cm) × 0.6345 / (120 cm × 50 cm). After tobacco leaves matured, they were harvested and cured separately by plot. Cured leaf yield was recorded, and leaves were professionally graded according to the National 42-Grade Standard for Flue-Cured Tobacco (GB 2635—92) to determine output value, average price, and proportion of high-quality tobacco.

1.3.2 Soil Water Content

Using a soil auger, one sampling point was established between two representative tobacco plants in each plot during the rosette stage (30 days after transplanting), early vigorous growth stage (45 days), late vigorous growth stage (60 days), and early maturation stage (75 days). Soil samples were collected from depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, and 50–60 cm. Soil gravimetric water content was determined using the 105°C oven-drying method, with three replications per treatment.

1.3.3 Soil Physical Properties

During the vigorous growth stage (54 days after transplanting), one sampling point was established between two representative tobacco plants in each plot. Soil bulk density, total porosity, capillary porosity, and non-capillary porosity were measured at depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, and 50–60 cm using the core method [11], with three replications per treatment.

1.3.4 Root Spatial Distribution

During the squaring stage (65 days after transplanting), root samples were collected using a small cubic in-situ root-soil sampler [12] based on the "3D monolith" stratified spatial sampling method [13–14]. Sampling was conducted at 10 cm intervals to a depth of 60 cm, with nine soil blocks collected per layer centered on the tobacco plant. Each sampling unit consisted of a 10 cm × 10 cm × 10 cm soil block. White, fresh tobacco roots were manually extracted from each unit block, washed with static water, and weighed fresh. One representative plant was selected per plot for root sampling.

Root Depth Index (cm) = Σ[Average Depth of Each Layer (cm) × Percentage of Root Dry Weight in That Layer Relative to Total Root Weight] [15].

1.4 Data Processing and Analysis

Data processing and graphing were performed using Microsoft Excel 2007. Statistical analysis and significance testing ($P < 0.05$) were conducted using SPSS 17.0. SURFER 8.0 software was used for grid processing to generate contour maps and 3D wireframe diagrams.

2.1 Changes in Tobacco Leaf Area Index and Yield Under Different Tillage Depths

Flue-cured tobacco is a leaf-economic crop, and leaf area significantly influences yield. shows that during the rosette stage, leaf area index followed the order GS40 > GS30 > GS20, with significant differences among treatments, indicating that deep plowing importantly promoted early and rapid seedling growth. During the vigorous growth stage, the leaf area index remained GS40 > GS30 > GS20, but no significant difference existed between GS30 and GS20. As the growth stage progressed, differences in leaf area index among treatments gradually diminished.

From the perspective of economic indicators including yield, average price, output value, and proportion of high-quality tobacco, the order was GS40 > GS30 > GS20, with significant differences between GS40 and GS20 (). The output values under GS30 and GS40 reached 7.91×10^4 ¥ · hm^{-2} and 9.81×10^4 ¥ · hm^{-2}, respectively, representing increases of 9.0% and 35.1% compared with GS20. Yield increased by 7.0% and 27.3%, average price by 1.8% and 6.2%, and the proportion of high-quality tobacco by 10.4% and 24.4% relative to GS20. Deep tillage effectively improved both tobacco leaf yield and quality, increasing land productivity.

2.2 Soil Physical Properties Under Different Tillage Depths

Deep plowing effectively improved soil physical properties in the 0–40 cm layer of tobacco fields, with better amendment effects in the 20–40 cm subsurface layer than in the 0–20 cm surface layer, and essentially no effect on the 40–60 cm deep layer ([Figure 1: see original paper]). In the 20–40 cm subsurface layer, soil bulk density under GS30 and GS40 was 1.372 $g \cdot cm^{-3}$ and 1.356 $g \cdot cm^{-3}$, respectively, representing decreases of 8.4% and 9.4% compared with GS20. Total porosity and capillary porosity under GS30 and GS40 were significantly higher than under GS20, with total porosity increasing by 15.6% and 13.1%, and capillary porosity increasing by 25.8% and 24.8%, respectively. Soil physical properties showed increasing or decreasing trends along the soil profile: bulk density and non-capillary porosity increased with soil depth, while total porosity and capillary porosity decreased with depth.

[Figure 1: see original paper]

2.3 Changes in Soil Water Content Under Different Tillage Depths

Different tillage depths significantly affected the vertical distribution of soil moisture in tobacco fields. With few exceptions across growth stages and soil layers, soil water content followed the order GS40 > GS30 > GS20 ([Figure 2: see original paper]). Deep plowing significantly increased soil water content in the 0–20 cm surface layer during the rosette stage, with GS30 and GS40 showing increases of 7.2% and 14.0% compared with GS20. Deep plowing also significantly increased soil water content in the 20-40 cm subsurface layer during early vigorous growth, late vigorous growth, and early maturation stages. During early vigorous growth, GS30 and GS40 increased soil water content by 7.2% and 18.7% compared with GS20; during late vigorous growth, increases were 10.2% and 24.3%; and during early maturation, increases were 17.9% and 27.8%. Deep plowing enhanced soil water storage. During the rosette stage, soil water content decreased with depth; during early vigorous growth, it first increased then decreased with depth; during late vigorous growth and early maturation, water content across different soil layers was relatively similar among treatments. As the tobacco growth progressed, soil water content in the 0-20 cm layer showed a decreasing trend across treatments, while 20-30 cm layer water content first increased then decreased. Changes in 30-60 cm layer water content showed no clear pattern.

[Figure 2: see original paper]

2.4.1 Horizontal Distribution of Roots in Different Soil Layers

Different tillage depths significantly affected the spatial distribution characteristics of flue-cured tobacco roots. In the 3D wireframe diagram shown in [Figure 3: see original paper], the height of each point on the upper surface represents the magnitude of root fresh weight at different positions within the same soil layer. The diagram reveals that root fresh weight showed a single peak in the 0-30 cm soil layer and multiple peaks in the 30-60 cm layer. Across the 0-60 cm soil profile, total root fresh weight under GS30 and GS40 was 31.2% and 89.2% higher than under GS20, respectively, indicating that deep plowing promoted absolute root biomass increase. The effect of deep plowing on root fresh weight varied among soil layers, with greater differences observed in the 20-40 cm subsurface layer than in other layers. During the tobacco squaring stage, root fresh weight in the 20-30 cm layer under GS30 and GS40 was 88.6% and 130.9% higher than under GS20, respectively, while in the 30-40 cm layer, it was 211.3% and 238.9% higher.

[Figure 3: see original paper]

2.4.2 Root Distribution in the Soil Vertical Profile

Within the 0-60 cm vertical soil profile of tobacco fields, flue-cured tobacco root fresh weight first increased then decreased ([Figure 4: see original paper]). Over 98.2% of roots were distributed in the 0-40 cm soil layer, with 59.4%-69.3% of roots concentrated in the 10-20 cm layer. Compared with GS20, the iso-mass distribution lines under GS30 and GS40 were wider and deeper, encompassing larger areas. Root depth indices under GS20, GS30, and GS40 were 16.71 cm, 17.98 cm, and 17.47 cm, respectively, demonstrating that deep plowing not only significantly increased absolute root biomass but also promoted root growth into deeper soil layers, increasing the proportion of roots in lower soil layers.

[Figure 4: see original paper]

3.1 Effects of Deep Plowing on Soil Physical Properties

Shallow tillage layers, increased bulk density, reduced effective tillage soil volume, and thickened, upward-shifted plow pans have become major constraints to high yield and efficiency in Chinese crop production [16]. Long-term application of small-power shallow tillage machinery has increased soil bulk density in Southwest tobacco fields, reduced soil porosity and pore continuity, destroyed vertical uniformity of soil structure, decreased exchange values of soil water, nutrients, and oxygen, and delayed soil biological processes [17]. Soil tillage is the most common agricultural practice for optimizing soil physicochemical properties, creating favorable habitats for underground growth and aboveground morphological development [18]. Deep plowing functions to turn, loosen, mix, and break up soil. Proper deep plowing can break through compacted plow pan barriers [19], maintain a relatively loose and uniform state in the 0–35 cm soil layer [20], promote downward root elongation, and thereby create a suitable soil environment for crop growth and yield formation [21]. Additionally, deep plowing significantly increases water infiltration, reduces soil water evaporation, and enhances soil water storage [22]. In soils with thickened, upward-shifted plow pans, low porosity limits vertical water movement; deep tillage breaks plow pan barriers, increases effective pores, improves soil solid-liquid-gas phase ratios, and consequently enhances water infiltration and storage. This study demonstrated that deep plowing to 30-40 cm significantly reduced soil bulk density in the 20–40 cm subsurface layer by 8.4%–9.4% while significantly increasing total porosity and capillary porosity by 13.1%–25.8%. It also significantly increased soil water content in the 0–20 cm surface layer during the rosette stage and in the 20–40 cm subsurface layer during vigorous growth and early maturation. Ji et al. [23] reported that deep plowing significantly reduced soil penetration resistance and bulk density while markedly increasing soil water content and root length density in loam soils, consistent with our findings. Deep plowing in tobacco fields should be adapted to local conditions, gradually increasing tillage depth according to the thickness of the mature topsoil layer, while avoiding turning up subsoil into the tillage layer. In tobacco fields under tobacco-rice rotation, excessively deep plowing in a single operation should be avoided, as completely breaking the plow pan may cause water and nutrient leakage during the rice season.

3.2 Influence of Soil Physical Properties on Root Spatial Distribution

Among soil physical properties, soil bulk density reflects soil compactness and is closely related to water permeability, aeration, and root elongation resistance [24]. Mechanical resistance from compacted soil slows cell division in root meristematic tissue and shortens cell length, thereby affecting root growth and extension in soil, resulting in shorter, thicker roots that limit effective distribution in deep soil layers and reduce water and nutrient absorption [25–26]. Soil pores serve as migration channels, storage reservoirs, and activity venues for soil water, nutrients, air, and microorganisms. Greater total porosity indicates looser soil structure, better aeration, and more favorable conditions for root extension and distribution [13]. Capillary pores are sites of strong water storage and movement; higher capillary porosity enhances soil water-holding capacity and facilitates adequate water and nutrient absorption by roots [27]. Our results showed that compared with GS20, GS30 and GS40 significantly increased tobacco root biomass in the 20–40 cm subsurface layer by 103.5% and 144.0%, respectively, likely due to effective improvement of soil physical properties including bulk density, total porosity, and capillary porosity in this layer. Previous studies indicated that deep plowing and subsoiling break soil plow pans, aerate deeper soil layers, promote root elongation into deep soil, increase the number of primary lateral and adventitious roots, enhance utilization of deep soil water and nutrients, and consequently improve crop yield [2].

In the root-soil system, root development is a dynamic process of continuous response and adjustment to the external environment, closely related to soil bulk density and water-nutrient distribution [28]. As the primary organ for water absorption, roots must elongate toward moist soil to access more water; high water infiltration and storage in deep soil layers promote vertical root growth [29]. Our results demonstrated that deep plowing significantly increased soil water content in the 0–20 cm surface layer during the rosette stage, promoting early and rapid seedling growth. Simultaneously, deep plowing significantly increased soil water content in the 20–40 cm subsurface layer during vigorous growth and maturation stages, which facilitated downward root growth, increased the root depth index, alleviated root crowding in upper soil layers, and was important for optimizing root distribution in the soil vertical profile.

3.3 Influence of Root Spatial Distribution on Aboveground Growth and Development

Crop root size and spatial architecture determine the ability to explore and absorb dynamically variable soil resources, including mobile and immobile resources, and to compete for soil space, water, and nutrients [30]. The root system serves as a bridge between agricultural tillage practices and aboveground growth changes: tillage first affects soil structural characteristics and water-nutrient content, then influences root growth, spatial distribution, and physiological activity, subsequently affecting aboveground morphological development, and ultimately impacting crop yield and quality [31]. A well-developed, deeply and widely distributed root system forms the foundation for high photosynthetic efficiency, yield, and quality in crop populations. Root extension into deep soil layers facilitates absorption of deep soil water and nutrients, enhances root vigor, delays root senescence, and maintains water and nutrient supply to aboveground parts [32]. Our results indicated that deep plowing positively influenced tobacco leaf yield, average price, proportion of high-quality tobacco, and output value, likely by improving tobacco field soil quality, optimizing root spatial distribution, and promoting water-fertilizer absorption by tobacco plants.

Conclusion

The effects of tillage practices on the root-soil system and crop yield have been a research hotspot in recent years. This study demonstrated that deep plowing effectively improved soil physical properties, optimized flue-cured tobacco root spatial distribution, and increased tobacco leaf yield and output value in Southwest tobacco fields. Deep plowing significantly reduced soil bulk density in the 20–40 cm subsurface layer while significantly increasing total porosity and capillary porosity. Compared with conventional tillage, deep plowing significantly increased soil water content in the 0–20 cm surface layer during the rosette stage, facilitating early and rapid growth after transplanting. Additionally, deep plowing effectively increased underground root biomass, optimized root spatial architecture, increased the root depth index, and enhanced tobacco leaf yield and output value.

These findings indicate that deep plowing is a suitable tillage method for tobacco production in Southwest China. However, practical application should be adapted to local conditions, gradually increasing tillage depth based on the thickness of the original mature topsoil layer while avoiding turning up subsoil. In tobacco fields under tobacco-rice rotation, excessively deep plowing in a single operation should be avoided, as completely breaking the plow pan may cause water and nutrient leakage during the rice season. This study provides guidance for understanding the mechanisms of deep plowing in tobacco fields and for scientific tillage management.

References

[1] Zhang S H, Li S K. Report of Corn Industry Development in China and Abroad—2009 [M]. Beijing: China Agricultural Science and Technology Press, 2010: 111—113.
[2] Wang N, Lan J Q, Wang D W, et al. Effect of different plowing depths on growth-development, yield and quality of flue-cured tobacco [J]. Southwest China Journal of Agricultural Sciences, 2014, 27(4): 1737—1740.
[3] Xu T Y, Zhao Z X, Li Z H, et al. Effect of tillage depth on growth, nutrient uptake, yield and quality of flue-cured tobacco plant [J]. Acta Agronomica Sinica, 2009, 35(7): 1364—1368.
[4] Lynch J P. Root phenes for enhanced soil exploration and phosphorus acquisition: Tools for future crops [J]. Plant Physiology, 2011, 156(3): 1041–1049.
[5] Pagès L. Links between root developmental traits and foraging performance [J]. Plant, Cell & Environment, 2011, 34(10): 1749–1760.

[6] Zhang X Y. Regulating mechanisms for improving farmland water use efficiency [J]. Chinese Journal of Eco-Agriculture, 2013, 21(1): 80−87.
[7] Cao Q J, Jiang X L, Yang F T, et al. Changes of root biologic properties during senescence after anthesis of spring maize under subsoiling treatment [J]. Journal of Maize Sciences, 2014, 22(5): 86−91.
[8] Jabro J D, Iversen W M, Stevens W B, et al. Physical and hydraulic properties of a sandy loam soil under zero, shallow and deep tillage practices [J]. Soil and Tillage Research, 2016, 159: 67-72.
[9] Gronle A, Lux G, Böhm H, et al. Effect of ploughing depth and mechanical soil loading on soil physical properties, weed infestation, yield performance and grain quality in sole and intercrops of pea and oat in organic farming [J]. Soil and Tillage Research, 2015, 148: 59-73.
[10] Bogunović I, Kisić I, Jurisić A. Soil compaction under different tillage system on Stagnic Luvisols [J]. Agriculturae Conspectus Scientificus, 2014, 79(1): 57−63.
[11] Institute of Soil Science, Chinese Academy of Sciences. Soil Physical and Chemical Analyses [M]. Shanghai: Shanghai Scientific and Technical Publishers, 1978: 512−514.
[12] Zhao M. The Crop Yield Performance and High Yield Technology [M]. Beijing: China Agriculture Press, 2013: 304−308.
[13] Wang X B, Hou H P, Zhou B Y, et al. Effect of strip subsoiling on population root spatial distribution of maize under different planting densities [J]. Acta Agronomica Sinica, 2014, 40(12): 2136−2148.
[14] Zha L, Xie M L, Zhu M, et al. Effects of ridge-cultivation and plastic film mulching on root distribution and yield of spring maize in hilly area of central Sichuan basin, China [J]. Chinese Journal of Applied Ecology, 2016, 27(3): 855−862.
[15] Tang S H, Xu P Z, Zhang F B, et al. Influence of single basal application controlled-release fertilizer on morphologic development of root system and lodging resistance of rice [J]. Plant Nutrition and Fertilizer Science, 2006, 12(1): 63−69.
[16] Wang C T, Li S K. Assessment of limiting factors and techniques prioritization for maize production in China [J]. Scientia Agricultura Sinica, 2010, 43(6): 1136−1146.
[17] Whalley W R, Dumitru E, Dexter A R. Biological effects of soil compaction [J]. Soil and Tillage Research, 1995, 35(1/2): 53-68.
[18] Xu D, Mermoud A. Topsoil properties as affected by tillage practices in North China [J]. Soil and Tillage Research, 2001, 60(1/2): 11-19.
[19] Munkholm L J, Schjønning P, Rasmussen K J. Non-inversion tillage effects on soil mechanical properties of a humid sandy loam [J]. Soil and Tillage Research, 2001, 62(1/2): 1−14.
[20] Birkás M, Jolánkai M, Gyuricza C, et al. Tillage effects on compaction, earthworms and other soil quality indicators in Hungary [J]. Soil and Tillage Research, 2004, 78(2): 185-196.
[21] Borghei A M, Taghinejad J, Minaei S, et al. Effect of subsoiling on soil bulk density, penetration resistance and cotton yield in northwest of Iran [J].

International Journal of Agriculture and Biology, 2008, 10: 120-123.
[22] Lampurlanés J, Angás P, Cantero-Martínez C. Root growth, soil water content and yield of barley under different tillage systems on two soils in semiarid conditions [J]. Field Crops Research, 2001, 69(1): 27-40.
[23] Ji B, Zhao Y, Mu X, et al. Effects of tillage on soil physical properties and root growth of maize in loam and clay in central China [J]. Plant Soil and Environment, 2013, 59(7): 295-302.
[24] Hope G D. Effects of Mechanical Site Preparation on Soil and Foliar Nutrients in the Drier Subzones of the IDF, MS and ESSF Zones-Project 3.50 [M]. Victoria BC: Res. Dev. Agree., 1991: 193.
[25] Bécel C, Vercambre G, Pagès L. Soil penetration resistance, a suitable soil property to account for variations in root elongation and branching [J]. Plant and Soil, 2012, 353(1/2): 169-180.
[26] Hou P, Chen X P, Cui Z L, et al. Potential maize yield realization and related driving factors in four typical soils [J]. Chinese Journal of Eco-Agriculture, 2012, 20(7): 874-881.
[27] Zhang X B, Shangguan Z P. Effect of human-induced disturbance on physical properties of soil in artificial *Pinus tabulaeformis* Carr. forests of the Loess Plateau [J]. Acta Ecologica Sinica, 2006, 26(11): 3685—3695.
[28] Whalley W R, Watts C W, Gregory A S, et al. The effect of soil strength on the yield of wheat [J]. Plant and Soil, 2008, 306(1/2): 237-247.
[29] Muñoz-Romero V, López-Bellido L, López-Bellido R J. The effects of the tillage system on chickpea root growth [J]. Field Crops Research, 2012, 128: 76-81.
[30] Smith S, De Smet I. Root system architecture: Insights from Arabidopsis and cereal crops [J]. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 2012, 367(1595): 1441-1452.
[31] Zhu X D, Chen X L, Liu Y T, et al. Growth and distribution of maize roots in soil [J]. Journal of Laiyang Agricultural College, 1991, 8(1): 15—19.
[32] Wang K J, Zheng H J, Liu K C, et al. Evolution of maize root distribution in space-time during maize varieties replacing in China [J]. Acta Phytoecologica Sinica, 2001, 25(4): 472—475.

Note: Figure translations are in progress. See original paper for figures.